Isobaric-spin violation in the reaction $^{10}B(d, d')^{10}B$†

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The reaction $^{10}B(d,d')^{10}B$ was investigated to determine the isobaric-spin violation in exciting the lowest $T=1$ state of ^{10}B at an excitation energy of 1.74 MeV. The extent and nature of the isobaric-spin-forbidden reaction was obtained by measuring yield curves at laboratory angles of 30, 45, and 77°, using deuteron bombarding energies from 5 to 12 MeV and at 140° from 6.5 to 16 MeV. Simultaneously, data were obtained on the nearby isobaric-spin-allowed $T=0$ state at 2.15 MeV. Generally, broad structure dominates the excitation functions at all angles but tends to disappear at higher bombarding energies. Angular distributions of deuterons leading both to the $T=0$ and $T=1$ states were obtained at five bombarding energies between 6.5 and 12.0 MeV. The angular distributions both for the forbidden ($T=1$) and allowed ($T=0$) state are characterized by a trend to forward peaking with increasing bombarding energies although much less so for the $T=1$ state. The total cross sections were measured, and the ratios of the forbidden yield to allowed yield were found to decrease linearly from 0.69% at 6.5 MeV to 0.16% at 12 MeV. In an attempt to describe the angular distributions in terms of a direct-reaction mechanism, distorted-wave Born-approximation (DWBA) calculations were performed assuming collective excitations for the residual nucleus. No clear physical interpretation could be derived from these calculations. Indications are that the reaction $^{10}B(d,d')^{10}B$ proceeds through states very high in the compound nucleus ^{12}C, where the isobaric-spin violation originates in Coulomb mixing of $T=1$ and $T=0$ states of the same spin and parity. In view of the very small yield of deuterons leading to the lowest $T=1$ state in ^{10}B, and in view of the background difficulties anticipated and experienced, a specialized charged-particle detection system was used, consisting of a position-sensitive gas proportional counter mounted on the focal surface of a broad-range magnetic spectrograph. This constitutes the first observation of the lowest $T=1$ state in ^{10}B by the present reaction.

[NUCLEAR REACTIONS $^{10}B(d,d')$, $E=5$–16 MeV; measured $\sigma(E,\theta)$; ratio isobaric-spin allowed-forbidden. Enriched targets. DWBA analysis; $\theta=10$–150°.]

INTRODUCTION

It is well known that the symmetry implied by the charge independence of nuclear forces leads to a conservation law for isobaric spin (T) in nuclear reactions.[1] Reactions such as $^{10}B(d, d')^{10}B$ should not proceed to $T=1$ states since the ground states of both the deuteron and ^{10}B have $T=0$. Many violations of the selection rule have been observed for different reactions on various light nuclei. Early work was summarized in Ref. 2 and more recent work is referred to in the following. It is remarkable, however, that measurable yield to the lowest $T=1$ state of ^{10}B by inelastic deuteron scattering has not been seen. This state in ^{10}B at 1.74 MeV is the well-known $T_z=0$ member of the $T=1$ isobaric triad whose other members are the ground states of ^{10}Be and ^{10}C. The $T=1$ character has been confirmed by previous investigations, including the inelastic scattering of deuterons. The earliest attempt to observe the 1.74-MeV state using the reaction $^{10}B(d, d')^{10}B$ was made by Bockelman *et al.*[3] and they concluded that the conservation of isobaric spin could account for the failure to excite this state whose existence had been firmly established by Ajzenberg[4,5] in the reaction $^{9}Be(d, n)^{10}B$, by Buechner *et al.*[6] and by Craig, Donahue, and Jones[7] in the reaction $^{10}B(p, p')^{10}B$.

The only other careful attempt to observe this state by deuteron inelastic scattering was that of Armitage and Meads.[8] They once again attributed a $T=1$ nature to the 1.74-MeV state and also to the level at 5.17 MeV because of the absence of yield in both the $^{10}B(d, d')^{10}B$ and $^{12}C(d, \alpha)^{10}B$ reactions. Subsequent investigations and other evidence[1,9] confirm the $T=1$ character of these states. In both of the $^{10}B(d, d')^{10}B$ investigations cited only upper limits on the intensity of the isobaric-spin-forbidden yield were quoted (<1.5% of that to the nearest $T=0$ state at 2.15 MeV). Subsequently, the lowest $T=1$ state in ^{10}B has been observed with the isobaric-spin-forbidden reaction $^{12}C(d, \alpha)^{10}B$ by several investigators including Meyer-Schützmeister, von Ehrenstein, and Allas,[10] Jänecke *et al.*,[11] von Ehrenstein *et al.*,[12] Smith,[13] and Jolivette[14] over a very large energy range.

The purpose of the present study was, then, to make the first observation of the lowest $T=1$ state in ^{10}B by deuteron inelastic scattering and to make quantitative measurements on the energy dependence of the cross section to this state through a series of angular distributions and to compare this energy dependence to that of the allowed ($T=0$) state at 2.15 MeV. Additional information on the possible intermediate structure of the $d+{}^{10}B$ system was sought through several excitation functions leading to the same two final states. Owing to the low yield to the $T=1$ state, only a broad survey of the energy and angle surface was made to examine the general features of the reaction, rather than a detailed one which might have been amenable to fluctuation analysis.[15] For the latter study much finer energy steps are needed. Furthermore, the large number of degrees of freedom owing to the high spin of the ^{10}B ground state (3+) makes this a poor case for such an analysis.[16]

The isobaric-spin impurity which is the square of the amplitude of the $T=0$ state mixed into the $T=1$ state, is taken to be proportional to the measured ratio of the total cross section of the $T=1$ state to that of a $T=0$ state at comparable excitation. The proportionality constant is given approximately by the ratio $(2J_f+1)$ for the $T=1$ state to $(2J_f+1)$ for the $T=0$ state, where the J_f's are the spins of the two final states in question: 0 and 1, respectively. Thus the impurity is approximately 3 times the measured total cross section ratio.

An observed violation of isobaric spin may be attributed to Coulomb mixing of $T=1$ states into $T=0$ states (of the same spin and parity) in the compound nucleus as well as in both the initial and final states. MacDonald,[17] however, has calculated that the isobaric-spin impurity of the ground states and low excited states of light nuclei should be very small, too small to explain violations of the magnitude which are observed. The amount of mixing depends on the number and proximity of states having the same spin and parity as the one in question. In the case of ^{10}B where the lowest $T=1$ state has $J^\pi=0^+$, there are no known $J^\pi=0^+$, $T=0$ states up to an excitation energy of ≈20 MeV so that any observation of isobaric-spin violation in the reaction $^{10}B(d, d')^{10}B$ cannot be explained in terms of final-state impurity. For low excitations in the compound nucleus the spacing between compound states of the same spin and parity but different T is large compared to the average Coulomb matrix element connecting such states (static criterion).[18,19] Similarly, for high excitation energy in the compound nucleus where states decay before there is time for appreciable mixing, isobaric spin should again be a good quantum number (dynamic criterion). At intermediate excitation where neither of these conditions is met, the isobaric-spin violation should be maximal, if the reaction indeed proceeds through the compound nucleus. Some investigators have attributed direct mechanisms to some of these reactions, especially (d, α) at high deuteron bombarding energies. Such direct-reaction interpretations in (d, α) reactions however, have not been without criticism and the alternative compound-nuclear mechanism has been proposed.[13]

Other direct-reaction mechanisms which have been proposed do not depend on the particular reaction, but rather on the initial state. It is proposed that isobaric-spin impurities are introduced in $T=0$ projectiles such as the deuteron or α particle through the polarization of the projectile in the Coulomb field of the target nucleus. Such polarization mixes $T=1$ components into the deuteron (or α particle) by a spin-flip process or otherwise. The suggestions of both Drachman[20] and Griffy[21] are of this type, depending on the initial system only, independent of the bombarding energy. Both estimates may be regarded as predicting upper limits only on the isobaric-spin impurity even at rather high (>10 MeV) bombarding energies.

At zero bombarding energy for the deuteron, the separation energy of $d+{}^{10}B$ in the compound nucleus ^{12}C is 25.188 MeV so that there is a high excitation energy, if indeed such a compound system is formed. The region of this investigation is characterized by wide overlapping levels in the compound nucleus and the isobaric-spin violation is expected to be small because of the short lifetime of these states. In fact because of the short lifetime involved, it was hoped that the present experiment would be amenable to direct-reaction analysis and to a quantitative determination of the direct-reaction contribution, if any existed.

EXPERIMENTAL PROCEDURE

Deuteron beams were supplied by the FN tandem accelerator and beam currents were generally 1 to 2 μA. The 90° beam-analyzing magnet had been calibrated by elastic scattering[22] and the calibration confirmed by a careful proton resonance measurement on $^{16}O(E_R=12\,714$ keV).[23] The geometric energy resolution of the analyzer was usually 0.1% but normally the stabilizer system holds the terminal voltage fluctuation to less than the geometric resolution.

Targets were prepared from ^{10}B (enriched to 96.5%) obtained from Oak Ridge National Laboratory. The best targets in terms of thickness and stability were obtained using a modification[24] of the electron bombardment procedure suggested by Varian Associates for their single crucible "*e*-gun." The most suitable and durable targets had a backing of a thin layer of Formvar on a 5-μg/cm^2 carbon foil.[25] Fortunately a modest amount of carbon and oxygen can be tolerated since there are no inelastic groups at low excitation energy from these elements. A great deal of carbon and/or oxygen can be harmful, however, by contributing additional background from low-energy tailing of the elastically scattered deuterons. The target used for most runs had a thickness of 85 μg/cm^2,[26] which gave a deuteron energy loss of ≈10 keV at the lowest deuteron bombarding energies.

The extremely low yield of deuterons to the $T=1$ state, the high yield of deuterons from elastic processes producing background in the region of the $T=1$ state, and the extremely high yield of other particle types from competing reactions set the requirement for a high-resolution charged-particle identification system. Conventional techniques such as nuclear track plates or small position-sensitive solid-state detectors in spectrographs are inadequate for a study over a large energy and angle range, while in-chamber solid-state detectors have particle identification problems. If high resolution is not required, solid-state counter telescopes may be used. We used a single-wire 40-cm-long position-sensitive gas proportional counter of the Borkowski and Kopp type[27,28] (whose characteristics have been described by Jolivette, Stocker, and Hrejsa[29]) in the 50-cm broad-range magnetic spectrograph. This combination of a high-resolution magnet and particle identification with the proportional counter (through the energy loss in the counter gas) allowed us to make the first definitive observations of the 1.74-MeV ($T=1$) state in ^{10}B by deuteron inelastic scattering.

Excitation functions for both the $T=0$ and $T=1$ states were taken at laboratory angles of 30, 45, 77, and 140°, in energy increments of 250 keV for deuteron bombarding energies (E_d) from about 4 MeV to about 12 MeV. The 140° excitation function extended up to $E_d=16$ MeV. Angular distributions of deuterons from these levels were taken at $E_d=6.5$, 7.0, 9.0, 10.5, and 12.0 MeV, with a minimum of about 12 points per angular distribution. Deuterons from the 1.74- and 2.15-MeV states were recorded simultaneously. This simultaneous detection is possible because of the large range in magnetic rigidity covered by the proportional counter, namely 1.14:1.

Particle identification is given by a pulse from the insulated case of the detector. This pulse is proportional to the energy loss in the counter gas which is a mixture of 90% argon and 10% methane. The particle of interest was selected by a gate on these case pulses. A block diagram of the electronics is shown in Fig. 1.

From known energies of reaction products (gen-

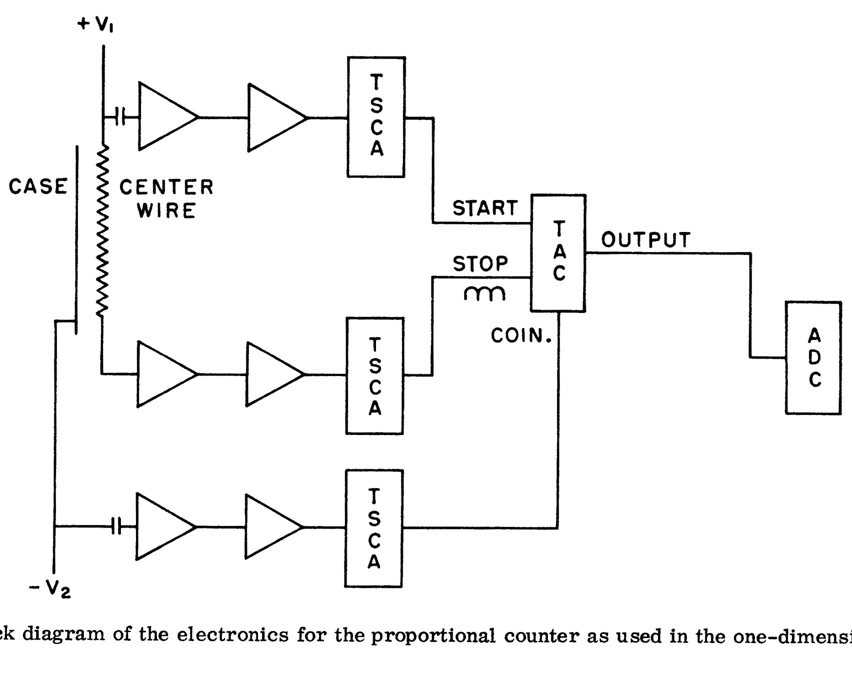

FIG. 1. Block diagram of the electronics for the proportional counter as used in the one-dimensional mode.

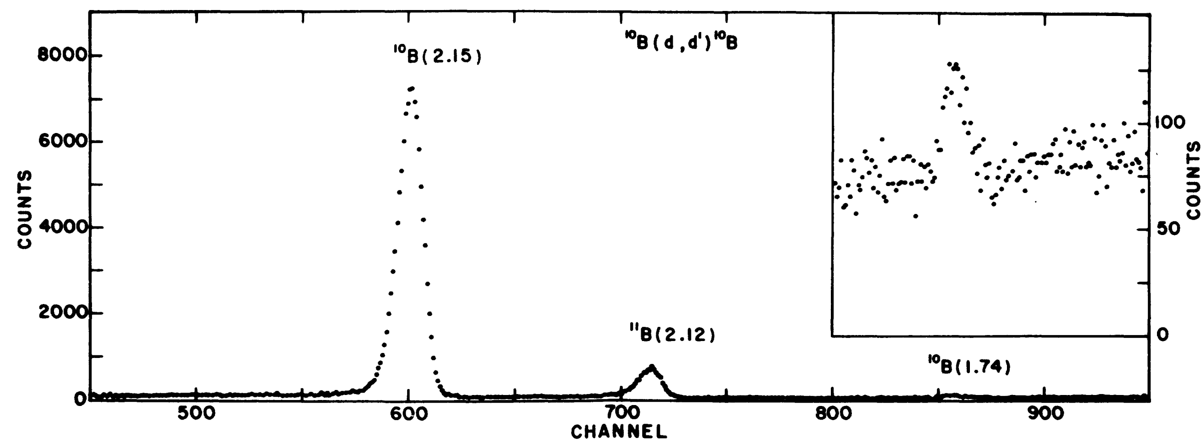

FIG. 2. Position spectrum of deuterons for $E_d = 7.0$ MeV, $\theta_{lab} = 77°$. The groups are labeled by their excitation energy in MeV in the indicated residual nuclei. The inset shows the 1.74-MeV state on a vertically expanded scale.

erally deuterons to the 2.15- and 0.72-MeV states of ^{10}B) and from the known magnetic field of the spectrograph, a calibration curve of analyzer channel versus radius of curvature of the particle trajectories is constructed, and is used to determine the expected channels for the weak deuteron group from the $T=1$ state at 1.74 MeV. The value of a reliable calibration appears when the group of interest is indiscernible above background or when several peaks occur in the position spectrum and their identification is not obvious. The width of the ever-present contaminant group corresponding to the 2.12-MeV state in ^{11}B is usually sufficient to indicate the appropriate channels for summation for the 1.74-MeV state. A monitor detector was placed at $\theta_{lab} = 135°$ and the reaction $^{10}B(d,p)^{11}B$(g.s.) was used for relative normalization among the successive angles of a given angular distribution. The target thickness was determined by comparing yields of elastically scattered deuterons from ^{10}B with those of Fitz, Jahr, and Santo[26] taken at a bombarding energy of 11.8 MeV. The relative uncertainty in these target thickness measurements was about 8% whereas their absolute uncertainty was about 25%, so that the latter figure is the minimum value for the uncertainty of our absolute differential cross sections. Further independent checks on the absolute solid angle were carried out. In addition, comparisons to the absolute differential-cross-section measurements of Barz *et al.*,[30] of Schiffer *et al.*,[31] and of Hinds and Middleton[32] were made for the $^{10}B(d,p)^{11}B$ (g.s.) reaction. Our measured target thickness gave consistent results. More complete numerical details are given in Ref. 33.

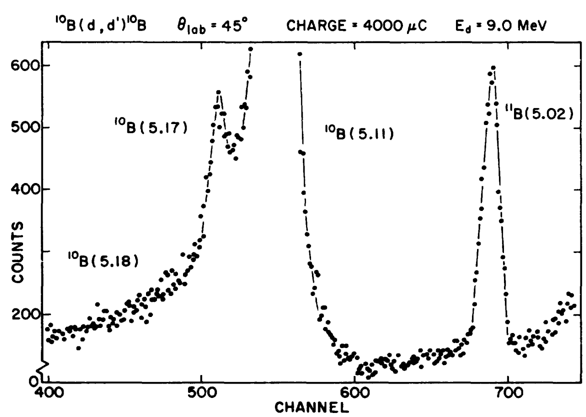

FIG. 3. Position spectrum of deuterons for $E_d = 9.0$ MeV, $\theta_{lab} = 45°$ showing the second $T=1$ state of ^{10}B at $E_x = 5.17$ MeV. Groups are labeled by their excitation energy in MeV in the indicated residual nuclei.

RESULTS

Figure 2 shows a deuteron position spectrum for $E_d = 7.0$ MeV and $\theta_{lab} = 77°$. The spectrum is dominated by the deuteron group leading to the ^{10}B 2.15-MeV state while the second strong peak corresponds to the 2.12-MeV state in ^{11}B. A vertically expanded view of the last 150 channels is shown in the inset, where the peak arising from the 1.74-MeV ($T=1$) state is clearly evident. In this case the intensity of the $T=1$ state compared to the $T=0$ state at 2.15 MeV is about 1%. As an extreme test of the spectrograph-proportional-counter system a single serious attempt was made to observe the second $T=1$ state in ^{10}B at an excitation energy of 5.17 MeV. The resulting position spectrum is shown in Fig. 3. The group labeled ^{10}B (5.17) is clearly evident and represents the first known observation of the second

$T=1$ state in ^{10}B by any isobaric-spin-forbidden reaction. The 5.18-MeV state (for which no group is clearly evident) is known to have large natural width ($\Gamma \approx 120$ keV) and is further known to be weakly excited in deuteron inelastic scattering.[8] The energy separation of the 5.11- and 5.17-MeV state is 52 keV,[34] with the unfortunate circumstance that the $T=1$ state lies higher in excitation than the $T=0$ state resulting in the weak state appearing in the tail of the strong one. Any systematic study of the second $T=1$ state of the kind undertaken with the lowest $T=1$ state would require substantially thinner targets (i.e., much less than 85 μg/cm^2) and much longer bombardments than the present 4000 μC. Hence it appears that any systematic study of the second $T=1$ state by deuteron inelastic scattering is impractical and no quantitative determinations on this state are reported.

Figure 2 illustrates the problem associated with a small yield on top of a large background. For independently determined background (B) and total count with peak (P), the net yield (Y) has an uncertainty (ΔY) which is the quadratic sum of the uncertainties in P and B; i.e., $\Delta Y=[(\Delta P)^2+(\Delta B)^2]^{1/2}=(P+B)^{1/2}$. For the 2.15-MeV state where the yield is large compared to the background, the uncertainty is about $(Y)^{1/2}$ since B is relatively small. In fact $\Delta Y/Y$ for the $T=0$ state is usually of the order of 1%. On the other hand, for the $T=1$ state when P and B may be comparable in magnitude, the statistical uncertainty is always a significant fraction of the $T=1$ yield.

Figures 4 and 5, respectively, show the excitation functions obtained for the 1.74- and 2.15-MeV states for $\theta_{lab}=30$, 45, 77, and 140°.

The region of excitation in the compound system ^{12}C is from about 29 to about 38 MeV. Uncertainties indicated for the 1.74-MeV excitation curve are statistical only. Uncertainties are not shown on the excitation function for the 2.15-MeV state since they are smaller than the data points.

The excitation functions for the isobaric-spin-allowed ($T=0$) state are characterized at all angles by rather broad, slowly varying structures. None of these structures has been studied in steps smaller than 250 keV, since sharp resonances are not expected at these excitation energies. The yield curves to the forbidden ($T=1$) state show somewhat similar structure to those of the $T=0$ state. Again, basically broad, slowly varying undulations predominate. The yield curve at $\theta_{lab}=140°$ has regions where deuterons from contaminants obscure the state of interest so that gaps do

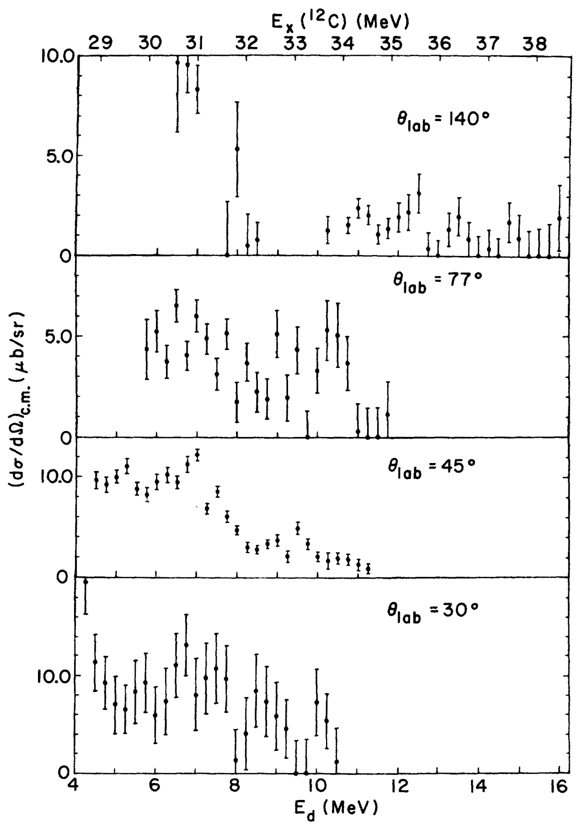

FIG. 4. Center-of-mass differential cross sections for the reaction ^{10}B(d,d')^{10}B (1.74 MeV, $J^\pi=0^+$, $T=1$) as a function of deuteron bombarding energy at the laboratory angles indicated.

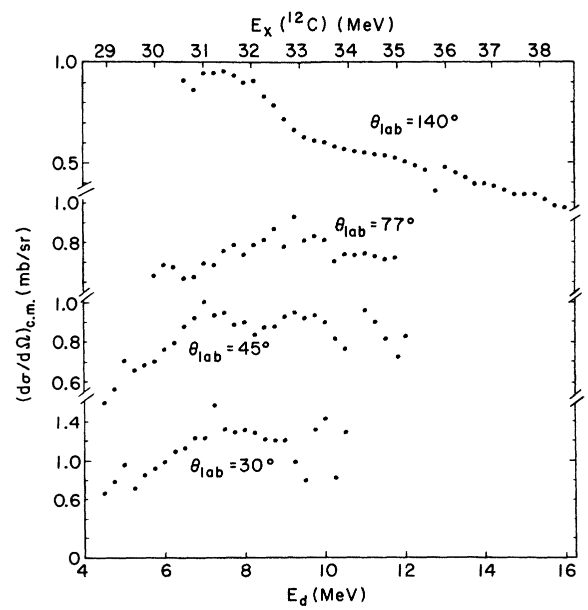

FIG. 5. Center-of-mass differential cross sections for the reaction ^{10}B(d,d')^{10}B (2.15 MeV, $J^\pi=1^+$, $T=0$) as a function of deuteron bombarding energy at the laboratory angles indicated.

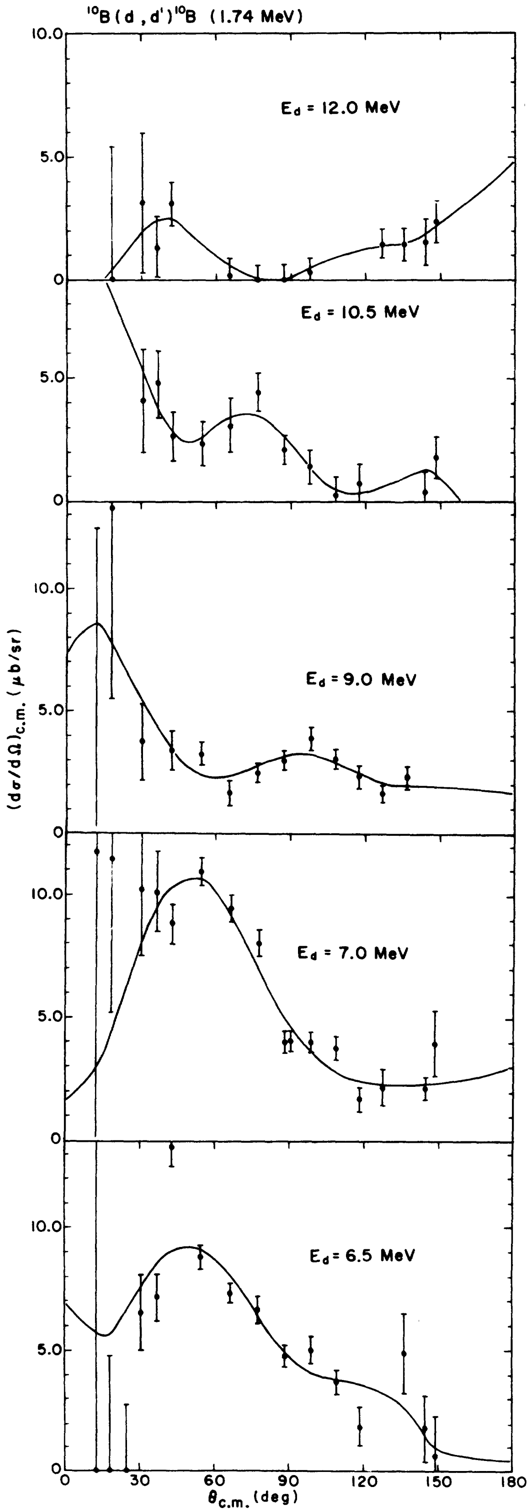

FIG. 6. Angular distribution of deuterons for the reaction $^{10}B(d,d')^{10}B$ (1.74 MeV, $J^{\pi}=0^{+}$, $T=1$) at the deuteron bombarding energies indicated. The solid lines are Legendre polynomial fits.

exist in the yield curve.

The experimental angular distributions are shown in Figs. 6 and 7 where again uncertainties indicated are statistical only. Attention should be given to the scales used for the excitation functions (Figs. 4 and 5) and angular distributions (Figs. 6 and 7). All the $T=0$ data have cross sections of the order of 1 mb, whereas the $T=1$ data have cross sections of the order of 1–10 μb.

The angular distributions of deuterons leading to the 2.15-MeV state in ^{10}B show a steady progression from an almost symmetric shape about $\theta_{c.m.}=90°$ at $E_d=6.5$ MeV to a forward-peaked structure with a secondary maximum around $\theta_{c.m.}=120°$ at $E_d=12.0$ MeV. Any such behavior is far less noticeable in the angular distributions to the

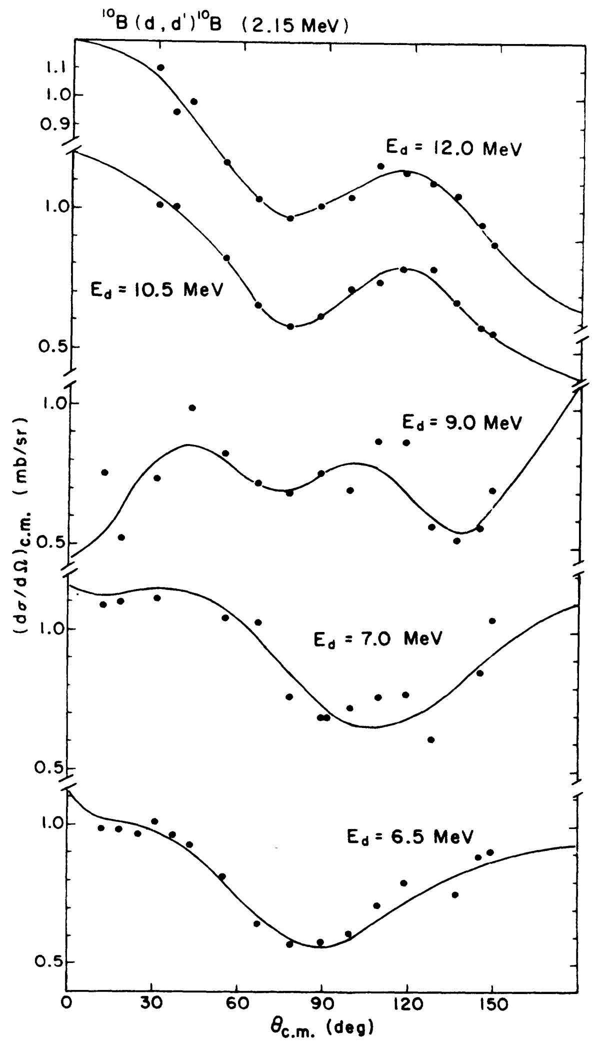

FIG. 7. Angular distribution of deuterons for the reaction $^{10}B(d,d')^{10}B$ (2.15 MeV, $J^{\pi}=1^{+}$, $T=0$) at the deuteron bombarding energies indicated. The solid lines are Legendre polynomial fits.

1.74-MeV state.

The angular distributions were fitted by least-squares with Legendre polynomials defined by

$$\frac{d\sigma}{d\Omega} = \sum_l A_l P_l(\theta).$$

The fits are shown as solid lines in the figures. A minimum in the χ^2 per degree of freedom as a function of polynomial order, l, was taken to represent the best fit. The value of l obtained in each case was in reasonable agreement with the outgoing orbital angular momentum estimate assuming a simple semiclassical description of the process. In no case was it found necessary to use polynomials higher than $l=5$.

The total cross section is $4\pi A_0$ where A_0 is the isotropic term of the Legendre coefficients. For each bombarding energy the total cross sections determined from the fits are listed in Table I along with the ratio (in %) of the total cross section for the forbidden (1.74-MeV) to the allowed (2.15-MeV) state. This is seen to vary from 0.69% at $E_d = 6.5$ MeV to 0.16% at $E_d = 12.0$ MeV. The total cross section ratio (in %) is illustrated in Fig. 8. It is worth noting that the total cross section was found to be very insensitive to the polynomial order of the fit.

As suggested earlier, an approximate value for the isobaric-spin impurity may be obtained from the measured total-cross-section ratio by multiplying this ratio by a statistical factor, which in the present case is just 3. The isobaric-spin impurity then varies from ≈2% at $E_d = 6.5$ MeV to ≈0.5% at $E_d = 12.0$ MeV.

DWBA ANALYSIS

It was one of the purposes of this investigation to try to determine the reaction mechanism(s) operative in the inelastic scattering in the energy range studied, and to determine whether direct-reaction contributions to the isobaric-spin violation were significant.

Low-lying states of a collective nature may be excited by a direct or one-step process. Even for initial and final states known to be of a significant single-particle nature, some collective enhancement such as that due to coupling-to-core oscillations is almost always present and may dominate the single-particle contribution.[35]

In the collective model many low-lying states arise from oscillations in shape about a spherical mean or from rotations of a deformed shape. This suggests extending the optical model to include nonspherical potentials. The nonspherical parts of the potential are then able to induce inelastic scattering to these collective vibrational or rotational states.

Calculations were carried out in the framework of the distorted-wave Born approximation (DWBA). The theory for excitation of collective states by direct inelastic scattering has been given by Tobocman[36] and Satchler.[37] The basic assumptions are that the initial and final nuclear states differ only in the degree of shape oscillation or rotation, that the inelastic transition is a simple one-step process, and that the relative motion of the projectile and target nucleus as well as residual nucleus may be described by distorted waves, which are calculated using an optical potential for elastic scattering at the appropriate energies. The transition then is one of elastic scattering in which the inelastic or reaction events may be treated as perturbations.

TABLE I. Total cross sections (σ_T) in μb for the 1.74- and 2.15-MeV states and their ratio.

E_d (MeV)	$\sigma_T(1.74)$	$\sigma_T(2.15)$	$\frac{\sigma_T(1.74)}{\sigma_T(2.15)}$ %
6.5	64.6±3.4	9370±100	0.69±0.04
7.0	68.5±3.0	11 000±120	0.62±0.03
9.0	38.8±3.8	9680±130	0.40±0.04
10.5	28.9±3.8	9470±120	0.31±0.04
12.0	14.6±3.3	8900±110	0.16±0.04

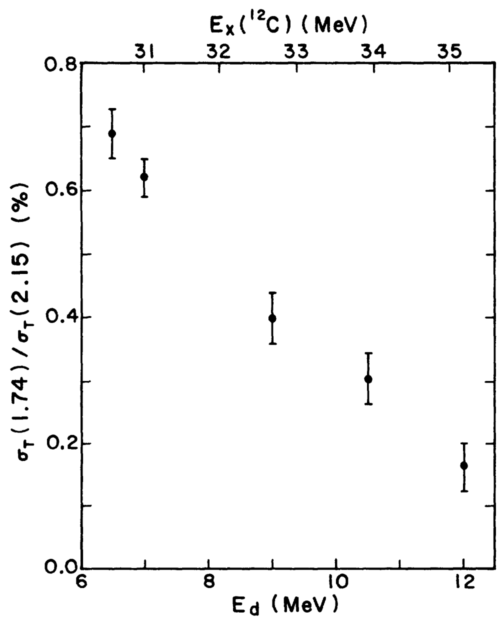

FIG. 8. Total cross section ratio (%) of inelastic deuterons to the 1.74-MeV state in ^{10}B compared to the 2.15-MeV state, as a function of deuteron bombarding energy.

The DWBA program DWUCK[38] calculates a "reduced" cross section $\sigma_L(\theta)$ for a given multipole order (or angular momentum transfer) L which is related to the experimental differential cross section by

$$d\sigma/d\Omega = \frac{2J_f+1}{2J_i+1} \sum_L \frac{1}{2L+1}\, \beta_L{}^2 \sigma_L(\theta),$$

where J_i and J_f are the spins of the initial and final states and β_L is the deformation parameter. The sum extends over all the multipole deformations allowed by the vector-coupling relationships, but because of the parity restriction [the parity change is given by $(-1)^L$] will consist of either all odd or all even terms

Some success using such a collective-model description of inelastic scattering by light nuclei has been achieved by Fitz, Jahr, and Santo[26] in the inelastic scattering of deuterons by ^{12}C leading to the 4.44-MeV state and by ^9Be leading the 2.43-MeV state. Indeed one might expect that in these cases such predictions would be suitable in view of the more favorable spin sequences: $0^+ \to 2^+$ in ^{12}C and $\frac{3}{2}^- \to \frac{5}{2}^-$ in ^9Be. Bassel *et al.*[35] found surprisingly good agreement between their DWBA prediction and experimental data from $^9Be(\alpha, \alpha')^9Be(2.43$ MeV) using 48-MeV α particles. They also describe the 2.43-MeV state as the $J = \frac{5}{2}$ member of the $K = \frac{3}{2}$ ground-state rotational band. A deformation parameter $\beta_2 = 0.8$ was extracted from the DWBA comparison to their data. Watson *et al.*[39] found a large cross section to the 6.04-MeV state in ^{10}B in proton inelastic scattering. This state has $J^\pi = 4^+$, $T = 0$ and as such is thought to be a member of the $K = 3$ rotational band built on the ground state, which has $J^\pi = 3^+$, $T = 0$.

The success of the collective description in the cases cited above should, nevertheless, not be carried over to the present situation of low-lying states in ^{10}B without some physical justification. A rotational spectrum built on the ground state would have the spin and parity sequence 3^+, 4^+, 5^+ etc. Since none of the transitions with which we are dealing involves states of spins larger than 1, these low-lying excited states cannot belong to the ground-state rotational band. As has been mentioned, the 4^+ state at 6.04 MeV is the likeliest candidate for inclusion in a ground-state rotational spectrum. Another band could exist, built on one of these excited states, but hard experimental evidence is lacking.

Since the description of nuclei in terms of collective motion permits both rotations and vibrations, one might attribute a vibrational character to the low-lying states of ^{10}B. In such a vibrational spectrum the lowest quantum of collective excitation (one phonon) has a quadrupole deformation and carries an angular momentum of 2 units and positive parity.[40] Such single-phonon excitations would allow 3^+ to 1^+ transitions, allowing for some inversion of the spin sequence. For transitions from $J = 3$ to $J = 0$, we would require an octupole vibration which involves a parity change. This is inconsistent with the positive parities of the states in question, so the 0^+ state in ^{10}B cannot belong to a ground-state vibrational band.

Since there is no way to excite the 0^+ $(T = 1)$ state by a simple rotation or vibration, it cannot be a good collective state and the DWBA should not give physically meaningful predictions. There is, however, a possibility that the transition to the 1^+ $(T = 0)$ state may be described in both shape and magnitude by the DWBA calculation, providing the state is indeed of a collective nature.

The optical potential was the usual complex form with a spin-orbit term[26]

$$U(r) = V_C(r) - Vf(r) - iWg(r) - V_{so}h(r)(\vec{l} \cdot \vec{s})$$

where $V_C(r)$ is the Coulomb potential resulting from a uniform charge distribution of radius $1.3A^{1/3}$ fm and where

$$f(r) = (1 + e^x)^{-1},$$

$$g(r) = 4\frac{d}{dx'}(1 + e^{x'})^{-1},$$

$$h(r) = \left(\frac{\hbar}{m_\pi c}\right)^2 r^{-1} \frac{d}{dr}(1 + e^x)^{-1},$$

$$x = (r - r_0 A^{1/3})/a,$$

$$x' = (r - r_0' A^{1/3})/a'.$$

Here A is the mass number, $f(r)$ is of the Woods-Saxon form, $g(r)$ is of a Woods-Saxon derivative form and indicates surface absorption and a is the diffuseness or surface thickness factor. V and W are the depths of the real and imaginary parts of the complex potential and V_{so} is the magnitude of the spin-orbit potential which has the Thomas form.

The optical-model parameters used for the present calculation were the Type I Set of Fitz, Jahr, and Santo[26] which were extracted from fitting the elastic scattering of 11.8-MeV deuterons by ^{10}B. In addition, we allowed for some energy dependence in the real and imaginary well depths. Although this set did not give the best fit to their ^{10}B data, it was the most consistent set for elastic deuteron scattering on various light target nuclei. These parameters also gave the best results for inelastic scattering to the state at 0.72 MeV in ^{10}B.

A typical parameter set for the 2.15-MeV state at $E_d = 12.0$ MeV was: $V = 118.0$ MeV, $r_0 = 0.863$ fm, $a = 0.916$ fm, $W = 5.4$ MeV, $r_0' = 1.59$ fm,

$a' = 0.716$ fm, and $V_{so} = 6.0$ MeV.

For the transition from the ground state to the 2.15-MeV state, a spin and parity sequence of $3^+ \to 1^+$ is required, which is possible for L transfers of 2 and 4. One expects the successively higher L values to contribute less and less to the cross section since a more complex excitation is required for the higher multipoles. Thus calculations were performed using only $L=2$ for the 2.15-MeV state. Further, it should be pointed out again that in the collective model which is the basis for the DWBA code, a direct single-step transfer of $L=3$ from a 3^+ to a 0^+ state as required for the transition from the ground state to the 1.74-MeV state violates parity so that such a transfer cannot take place, according to the DWBA assumptions.

In order to compare the experimental and calculated cross sections directly we used published values of β_L for the 2.15-MeV state, which along with the known values of J_i, J_f, and L allow for no arbitrary scaling factor between experiment and calculation. Squier *et al.*[41] (in the inelastic scattering of 32-MeV ^{3}He by ^{10}B) deduced $\beta_2 = 0.36$ for the 2.15-MeV state, and this is the value which was used in our calculation. By way of comparison Vaucher, Alder, and Joseph[42] obtained $\beta_2 = 0.69$ for this state using the inelastic scattering of 14.1-MeV neutrons by ^{10}B but this measurement was less accurate than that of Squier *et al.*

The results of the DWBA calculation are shown in Fig. 9 for the 2.15-MeV state. Here again the solid points are the data and the solid lines are the DWBA predictions for fixed β_2, independent of bombarding energy. The dashed line for $E_d = 12.0$ MeV which corresponds to $\beta_2 = 0.61$, shows a better fit. This β_2 is close to the value found by Vaucher *et al.*

The DWBA predictions for the 2.15-MeV state do not appear to reproduce the shape of the data at all bombarding energies, although there does appear to be an improvement toward the higher energies. By contrast, the magnitude for the cross-section prediction agrees with the data better at the lower bombarding energies. The total cross sections to the 2.15-MeV state determined by the DWBA program decrease by about a factor of 2 from $E_d = 6.5$ MeV to $E_d = 12.0$ MeV, whereas the experimental results indicate a much lower decrease over this energy range.

The disagreement in the β_2 for the 2.15-MeV state as determined by Squier *et al.*[41] and by Vaucher, Alder, and Joseph[42] and the failure of the DWBA predictions to match the shapes of the present experimental angular distributions indicate that this state is probably not a good collective state. Even our determination of $\beta_2 = 0.62$ for the 0.72-MeV state ($J = 1^+$, $T = 0$) using the data of Fitz, Jahr, and Santo[26] at $E_d = 11.8$ MeV disagrees with the ^{3}He inelastic result (at $E_{^3\text{He}} = 32.46$ MeV) of $\beta_2 = 0.37$ suggesting that this state too does not

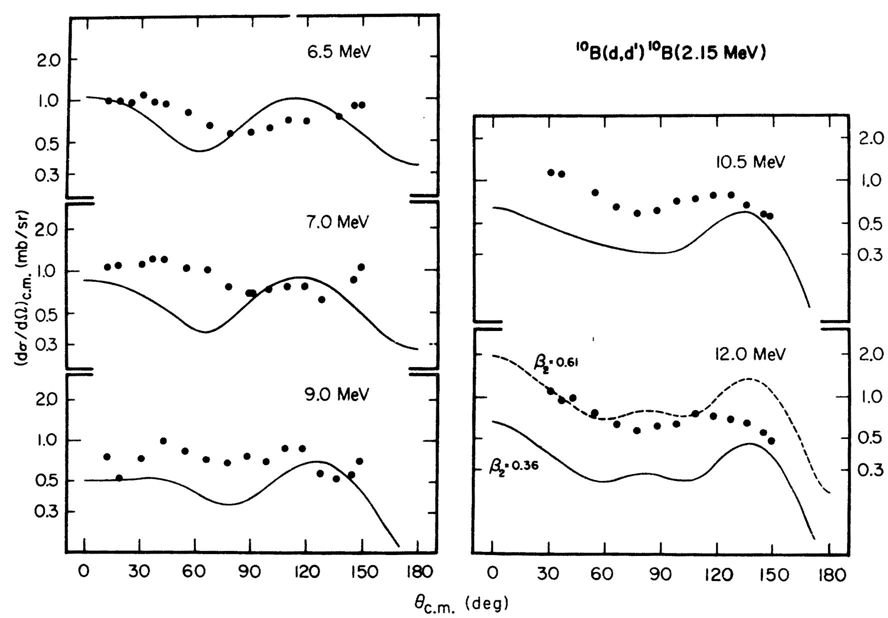

FIG. 9. Angular distributions for the reaction ^{10}B$(d,d')^{10}$B (2.15 MeV). The data points are shown as dots. DWBA calculations for the same reaction are shown as solid lines for $L=2$. For $E_d = 12.0$ MeV the same calculation but with $\beta_2 = 0.61$ is shown by a dashed line. See text for details.

have a simple collective nature.

Thus direct-reaction contributions to the 2.15-MeV state ($J = 1^+$, $T = 0$) in terms of collective excitations are probably small. The possibility still exists that other direct processes may contribute to the cross section.

One is drawn to the conclusion that while it is possible to use the collective-excitation formalism to analyze inelastic scattering results on light nuclei, the usual interpretation in terms of nuclear rotations and vibration must be treated with some caution. If true collective bands exist in ^{10}B they must be very complicated since interband transitions must be allowed for.[41] The existence of multiple deformation parameters β_L implies that an excited nuclear state may be characterized by a superposition of different collective modes so that the resultant motion of the nucleus is extremely complex. We are unable to deduce from this analysis a quantitative description of the direct-reaction contribution to the inelastic scattering cross section to either of the two final states in ^{10}B at 1.74 and 2.15 MeV.

PARTICLE CONFIGURATION

In order to assess the effect on the cross sections to the 1.74- and 2.15-MeV states of differences in the particle configurations of these two states, a review of results will be given for some isobaric-spin-conserving reactions, namely the inelastic scattering of nucleons and ^3He by ^{10}B. The particle configuration for the 1.74-MeV ($T=1$) state is generally agreed[43, 44] to belong to the $(p_{3/2})^6$ ground state configuration, whereas the 2.15-MeV ($T = 0$) state belongs to the excited configuration $(p_{3/2})^5(p_{1/2})^1$.

At $E_p = 7.6$ MeV and $\theta = 90°$ Bockelman *et al.*[3] found that the intensity ratio of the inelastic proton yield to the 1.74-MeV state compared to that to the 2.15-MeV state was ≈0.33, whereas at $E_p = 10.02$ MeV and $\theta = 90$ and 120° Armitage and Meads[8] measured this ratio to be about 0.12. The ratio of these total cross sections found by Schrank, Warburton, and Daehnick[45] at $E_p = 17.95$ MeV was ≈0.4. In view of the spins of the two final states the observed ratios might reasonably be adjusted by multiplication by a factor of 3. This would make the yields roughly comparable in the cases cited above.

A fairly complete study of the $^{10}B(p, p')^{10}B$ reaction between $E_p = 5$ and 16.5 MeV was carried out by Watson *et al.*[39] Total cross sections were determined for the five lowest-excited states and for the state at 6.04 MeV between $E_p \approx 5$ and 13 MeV for the 1.74-MeV state and from $E_p \approx 5$ to 16 MeV for the 2.15-MeV state. The range in the ratio of total cross sections of the $T=1$ to $T=0$ state was about 0.2 at 8 and 12 MeV to about 0.4 at 5 and 13 MeV. Thus with the adjustment for final-state spins these ratios become approximately consistent with equal populations for both the $T=0$ and $T=1$ states over almost the entire energy range.

Inelastic scattering of 14.1-MeV neutrons to several excited states of ^{10}B was carried out by Vaucher, Alder, and Joseph.[42] Their integrated cross section for the 1.74-MeV state is actually larger than that for the 2.15-MeV state by about 60%, but they do admit that the accuracy is fairly poor. Thus although no quantitative information can be deduced for these levels, the yields are of the same order of magnitude.

Absolute-cross-section measurements (±15 to ±20%) of ^3He inelastic scattering on ^{10}B at 10 MeV by Coop, Poate, and Titterton[46] at $\theta_{lab} = 40°$ indicated ratios of $T=1$ to $T=0$ yield of 0.17 and 0.19, respectively, not adjusted for spins. Partial angular distributions (back to 120°) using 32.5-MeV ^3He beams by Squier *et al.*[41] indicated a somewhat reduced yield for the $T=1$ state compared to the $T=0$ state, although no numerical ratios were given.

In general the nucleon inelastic scattering results indicate almost equal yields to the two states, favoring somewhat the $T=0$ state whereas the ^3He inelastic scattering suggests some reduction of yield to the $T=1$ state. Some small reduction in the yield ratio might then be expected in the (d, d') case owing to the configuration differences of the two states. This would imply a slight underestimate of the isobaric-spin impurity from the present results.

ISOBARIC-SPIN-VIOLATING REACTIONS

In this section, we compare the present (d, d') reaction to other isobaric-spin-violating reactions using $T=0$ incoming and outgoing particles: (1) with (d, α) and $(d, {}^6Li)$ experiments on the same target nucleus ^{10}B, that is, for the same incoming channel; (2) with other reactions such as $^6Li(^6Li, d)^{10}B$ forming the same compound system; (3) with other reactions such as $^{10}B(\alpha, \alpha')^{10}B$ in which the outgoing channel consists of ^{10}B plus a reaction particle having $T=0$. Some attention is also given to isobaric-spin-violating reactions in other nuclei, especially those which involve inelastic scattering of $T=0$ projectiles.

Comparison of the present (d, d') experiment to (d, α) reactions proceeding through the same compound state would be most interesting, but there is little common ground for such comparison. Whereas this investigation considered ratios of total cross sections of the forbidden to allowed states, the earlier investigations of Erskine and Browne[47] and Callender and Browne[48] compared intensity ratios of states at single angles only for a given energy. Aside from the case of the maximally mixed isobaric-spin states at 16.6 and 16.9 MeV in ^{8}Be, a comparison of the yield, made by Callender and Browne of the $T=1$ state at 17.6 MeV to the $T=0$ state at 18.1 MeV (both 1^+) showed a variation from about 20% at 6 MeV and $\theta_{lab}=30°$ to about 9% at 12 MeV and $\theta_{lab}=10°$. The present results for the total cross sections (adjusted for final-state spins) varied from 2% to 0.5% over the same energy range. In no case did an intensity ratio (at a given energy and angle) exceed 7.5%. The total cross-section measurement of Browne and Erskine[49] at $E_d=7.5$ MeV for the ^{10}B(d, α)^{8}Be reaction provides the only direct comparison to the entrance channel ^{10}B + d. They found that the total cross section to the 17.6-MeV state $J^\pi=1^+$, $T=1$) was 0.7 ± 0.2 mb, whereas in the present ^{10}B(d, d')^{10}B ($J^\pi=0^+$, $T=1$) reaction we measured only $\approx0.060\pm0.005$ mb (at about the same bombarding energy) which is more than a factor of 10 smaller than the (d, α) yield. Because of the final-state spins, 0^+ in the present case and 1^+ in the (d, α) case, one might expect about a factor $2J+1$ additional yield for the 17.6-MeV state (which has $J=1$) and taking this into account reduces the previous factor of 10 to about a factor of 3 to 4. One also notes that the ratio of yields for the 17.6-MeV ($T=1$) state to the 18.1-MeV ($T=0$) state was about 0.083 at 7.5 MeV as measured by Browne and Erskine, whereas in the present case the ratio of $T=1$ to $T=0$ yield was about 0.015 (adjusted for final spins). In comparing either the total cross section to isolated $T=1$ states in the different residual nuclei, or in comparing the individual $T=1$ to $T=0$ yield in the two reactions, one sees that the (d, α) reaction proceeds at a rate about 4–5 times that of the (d, d') at 7.5 MeV. The absence of more complete (d, α) data restricts the comparison to this case only. It thus seems that in the case of ^{10}B(d, d')^{10}B the yield ratios of $T=1$ states to $T=0$ states are significantly less than those in the ^{10}B(d, α)^{8}Be reaction at comparable bombarding energies. The general trend with energy of the present data is similar however to the limited (d, α) data, i.e., an almost monotonic decrease of $T=1$ to $T=0$ yield with increasing bombarding energy.

For the ^{10}B(d, ^{6}Li)^{6}Li reaction, Gutbrod, Yoshida, and Bock[50] reported no indication of yield (within their experimental uncertainties) to the $T=1$ state at 3.56 MeV in ^{6}Li for a deuteron bombarding energy of 19.5 MeV. Total cross sections at $E_{^6\text{Li}}=2.1$ MeV have been reported by Huberman, Kamegai, and Morrison[51] for the reaction ^{6}Li(^{6}Li, d)^{10}B leading to both the 1.74- and 2.15-MeV states. Although the deuterons corresponding to the 1.74-MeV state were not observed (within the experimental uncertainties), an upper limit to the total cross section of the $T=1$ state of less than 200 μb and a ratio of the total cross sections of less than 5% was given. Morrison[52] observed a measurable but small yield to the $T=1$ state at the same lithium bombarding energy at $\theta_{lab}=9.5°$ and suggested a heavy-particle stripping reaction mechanism and cluster model for the nucleus. Using the same incoming channel, ^{6}Li + ^{6}Li, Garvey, and Hiebert[53] observed no yield to the outgoing channel ^{6}Li + ^{6}Li (3.56 MeV) at $E_{^6\text{Li}}=63$ MeV. Their upper limit on the yield to the 3.56-MeV state was less than 1% of that to the allowed 2.18-MeV state.

In the ^{4}He inelastic scattering measurements of Coop, Poate, and Titterton[54] at $E_\alpha=10$ MeV and $\theta_{lab}=40°$ the upper limit to the intensity of the $T=1$ to $T=0$ state was 1.5%. At $E_d=10$ MeV and $\theta_{lab}=45°$ we measured the ratio to be about 0.23%. Since no angular distributions were taken in the (α, α') experiment no further meaningful comparisons are possible.

As mentioned earlier, the ^{12}C(d, α)^{10}B reaction leading to the 1.74-MeV state in ^{10}B has been the subject of several investigations. Meyer-Schutzmeister, von Ehrenstein, and Allas[10] found that the intensity to the $T=1$ state (1.74 MeV) was about 10% of that to the lowest $T=0$ states (ground state, 0.72 and 2.15 MeV) at $E_d=9$ MeV, while at $E_d=11$ MeV this ratio was 1–2%. These figures include the adjustment necessary for spin-inhibition factors. Jänecke *et al.*[11] investigated the same reaction between $E_d=13$ and 21 MeV. While no figures for the ratios of the total cross sections are given, peak cross sections between $E_d=13$ and 15 MeV at $\theta_{lab}=20°$ are of the order of 100 μb/sr. The data presented by von Ehrenstein *et al.*[12] were restricted to angular distributions for the $T=1$ state only between $E_d=14.0$ and 17.0 MeV. No total cross sections were reported. The very complete data reported by Smith[13] for $7.19<E_d<13.99$ MeV indicate ratios of total cross sections to the $T=1$ state compared to the nearby $T=0$ states to be about 3% between $E_d=9$ and 10 MeV, decreasing to about 1% at 11 MeV and remaining fairly constant ($\approx$1%) thereafter. When the ratios are adjusted for final-state spins, the results of Smith and Meyer-Schützmeister *et al.* are in fair agreement at their common bombarding energies. Once again the total cross section to the $T=1$ state is always significantly larger in the ^{12}C(d, α)-^{10}B reaction than in the present deuteron inelastic scattering case, ranging from a factor of 40:1 at

9 MeV to about a factor of 10:1 at 12 MeV. The intensive study of the $^{12}C(d, \alpha)^{10}B$ reaction by Jolivette[14] above $E_d = 14$ MeV is still in progress, but significant yields (up to 100 μb/sr) to the $T=1$ state persist up to $E_d = 16$ MeV.

The same general behavior in the total cross section is seen in the only other case of isobaric-spin violation by deuteron inelastic scattering reported to date, namely the $^{14}N(d, d')^{14}N$ (2.31 MeV, $J^\pi = 0^+$, $T = 1$ and 3.95 MeV, $J^\pi = 1^+$, $T = 0$) reaction reported by Duray and Browne.[55] An almost monotonic decrease with energy of the ratio of total cross sections was also seen by them, from about 9% at 6 MeV to 3% at 10 MeV, adjusted once again for final-state spins. Preliminary results of Kamykowski[56] indicate a continuation of this monotonic decrease up to $E_d = 15$ MeV in this reaction.

The other extensive investigation of an isobaric-spin-violating reaction using inelastic scattering was the $^{14}N(\alpha, \alpha')^{14}N$ reaction reported by Chesterfield and Spicer,[57] Tollefsrud and Jolivette,[58] and Chesterfield and Parker.[59] The findings of these investigations (each progressing to higher ^{18}F excitation energies) were that the isobaric-spin impurity remained large even at higher excitation energies in ^{18}F. Tollefsrud and Jolivette found the impurity to be ≈14% at $E_x(^{18}F) = 18$ MeV while differential cross sections as large as 200 μb/sr were still observed up to $E_x(^{18}F) = 23.5$ MeV.[57]

Where detailed comparisons are possible between the present and other isobaric-spin-forbidden reactions which have been extensively studied, several general features emerge:

(1) The total cross sections to the lowest $T = 1$ state in ^{10}B as observed in the present reaction are smaller than those observed in any of the other known isobaric-spin-violating reactions, especially those involving (d, α) reactions.

(2) The ratios of the total cross sections of the $T = 1$ to $T = 0$ states as reported in the present work are comparable to or smaller than any of the previously observed reactions.

(3) The general trend of the present data is in agreement with other studies made over wide energy ranges; namely, the total cross section to the $T = 1$ state decreases with increasing energy, whereas that to the $T = 0$ state remains fairly constant, reflecting a possible contribution from a direct-reaction mechanism at the higher energies.

The results of Kamykowski[56] for the $^{14}N(d, d')^{14}N$ reaction are both in qualitative and quantitative agreement with the present findings at comparable excitation energies in the respective compound systems.

REACTION MECHANISM

According to the predictions of Wilkinson[19] the results of the present experiment should be determined by the "dynamic criterion," i.e., the average Coulomb matrix element connecting $T = 0$ and $T = 1$ states in the compound nucleus should be much less than the average level width. As higher and higher excitation energies are reached in the compound nucleus, the average level width continues to increase, so that the compound system has more and more overlapping states. The excitation function then has a fairly smooth variation and prominent resonant structure has disappeared. This appears to be the case in the excitation functions of $^{10}B + d$. By and large, the yield curves of both the 1.74- and 2.15-MeV states have the same behavior. At the lowest bombarding energies there is some remnant of resonant structure, where individual levels may exist, but there is a progression to a rather featureless condition as the bombarding energy is increased. The passage from the region where the isobaric-spin violation is large to the one in which the "dynamic criterion" should be valid is estimated by Wilkinson to occur at 22–30 MeV in $4n$-type nuclei such as ^{12}C. That is, the isobaric spin should again become a "good" quantum number and the yield to the $T = 1$ state should decrease with energy. In view of the present data, this estimate is not unreasonable although possibly low. Of course in the system $^{10}B + d$ (corresponding to the large excitation energy of 25.188 MeV in ^{12}C at zero bombarding energy) there is probably no region where the isobaric-spin violation is large.

The region in which the "dynamic criterion" is valid can also be described by a "direct" mechanism. In the language of direct reactions, the characteristic interaction time is short compared to the time necessary for the Coulomb force to mix states of differing isobaric spin. The progression in the shape of the angular distributions (especially to the 2.15-MeV state) from approximately symmetric about $\theta_{c.m.} = 90°$ at 6.5 MeV to forward peaked at 12.0 MeV is not inconsistent with a qualitative direct-reaction mechanism description for inelastic processes.

In fact a combination of the two reaction mechanisms can also account for the total cross-section data. If the reaction leading to the $T = 0$ state is taken to be "direct," one expects an increase and then a slow decrease in the total cross section with increasing bombarding energy. The present data for the $T = 0$ state show a slowly decreasing total cross section above $E_d = 7$ MeV. However, it could be argued that the decrease in total cross section for the $T = 1$ state with increasing energy could be accounted for by purely compound process without any need to invoke a "direct" contribution.

As mentioned earlier, the direct-reaction estimates of both Drachman[20] and Griffy[21] based on a polarization of the incoming projectile by the Coulomb field of the target nucleus may be regarded as upper limits only, and in general are smaller than the experimental results.

Noble's hypothesis[60] concerning a complex heavy-particle exchange in inelastic scattering in the isobaric-spin-forbidden reaction does not seem applicable because of the absence of substantial forward or backward peaking in the differential cross section.

In general, for a compound-nuclear reaction one would expect some reduction in the total cross section as a function of increasing bombarding energy.[61] The result for the $T=1$ state is consistent with this but the $T=0$ state shows very little decrease in total cross section, suggesting possible direct-reaction contributions (which would tend to increase with bombarding energy above the direct-reaction threshold), although once again this is not a conclusive argument in favor of compound-nucleus formation.

Also of significance to the present discussion is the energy dependence of the angular distributions for both the $T=0$ and $T=1$ states. The steady progression to forward peaking in the $T=0$ state (and to a lesser degree in the $T=1$ state) seems to imply some component of direct reaction in the angular distribution. The work of Smith[13] in the $^{12}C(d, \alpha)^{10}B$ reaction indicates that up to $E_d=14$ MeV, there is no evidence of direct-reaction processes in any of the observed α-particle channels; that is, all evidence supports compound-nucleus formation even in the presence of forward-peaked angular distributions. Furthermore, the interpretation of direct-reaction-mechanism contributions as given by von Ehrenstein *et al.*[12] between $E_d=12$ and 17 MeV are refuted by Richards and Smith[62] who are able to give an explanation of the forward-peaked angular distributions in terms of a compound-nucleus picture. In the present case, the absence of data beyond $\theta_{c.m.}=150°$ makes any argument based on a forward-peaked angular distribution rather tenuous. Therefore it is somewhat hazardous to propose a direct-reaction mechanism solely on the basis of the shapes of limited angular distributions.

The same compound-nucleus picture has also been put forward consistently to explain the $^{16}O(d, \alpha)^{14}N$ data of Jolivette[63] and the $^{14}N(\alpha, \alpha')^{14}N$ data.[57-59] The evidence is also strong in the work of Hrejsa and Browne[64] in the $^{20}Ne(d, \alpha)^{18}F$ reaction as well as in the $^{14}N(d, d')^{14}N$ study of Duray and Browne.[55] Where evidence has been sought for direct or semidirect mechanisms, it has not been found conclusively. Indeed, aside from the controversy connected with the $^{12}C(d, \alpha)^{10}B$ reaction at selected energies, all reactions have been given such compound-nucleus interpretations. All cases known to date which involve inelastic scattering of $T=0$ projectiles by $T=0$ targets leading to $T=1$ residual nuclei have been interpretable in terms of a compound-nucleus process.

In the present $^{10}B(d, d')^{10}B$ work we see no unambiguous evidence favoring a direct-reaction mechanism to either the $T=0$ or $T=1$ final states in terms of collective excitations, although other direct-reaction processes may still exist contributing to the $T=0$ cross section, preferentially.

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

[2]C. P. Browne, in *Isobaric Spin in Nuclear Physics*, edited by J. D. Fox and D. Robson (Academic, New York, 1966), pp. 136–161, and references therein.

[3]C. K. Bockelman, C. P. Browne, W. W. Buechner, and A. Sperduto, Phys. Rev. 92, 665 (1953).

[4]F. Ajzenberg, Phys. Rev. 82, 43 (1951).

[5]F. Ajzenberg, Phys. Rev. 88, 298 (1952).

[6]W. W. Buechner, C. P. Browne, M. M. Elkind, A. Sperduto, H. A. Enge, and C. K. Bockelman, Phys. Rev. 87, 237A (1952).

[7]D. S. Craig, D. J. Donahue, and K. W. Jones, Phys. Rev. 88, 808 (1952).

[8]B. H. Armitage and R. E. Meads, Nucl. Phys. 33, 494 (1962).

[9]G. Morpurgo, Phys. Rev. 110, 721 (1958).
[10]L. Meyer-Schützmeister, D. von Ehrenstein, and R. G. Allas, Phys. Rev. 147, 743 (1966).
[11]J. Jänecke, T. Yang, R. M. Polichar, and W. S. Gray, Phys. Rev. 175, 1301 (1968).
[12]D. von Ehrenstein, L. Meyer-Schützmeister, J. E. Monahan, A. Richter, and J. C. Stoltzfus, Phys. Rev. Lett. 27, 107 (1971).
[13]H. F. Smith, Jr., Phys. Rev. C 6, 441 (1972).
[14]P. L. Jolivette, Bull. Am. Phys. Soc. 17, 464 (1972).
[15]T. Ericson and T. Mayer-Kuckuk, Annu. Rev. Nucl. Sci. 16, 183 (1966).
[16]G. M. Temmer, Phys. Rev. Lett. 12, 330 (1964).
[17]W. M. MacDonald, in *Nuclear Spectroscopy Part B*, edited by F. Ajzenberg-Selove (Academic, New York, 1960), pp. 932–959.
[18]A. M. Lane and R. S. Thomas, Rev. Mod. Phys. 30, 257 (1958).
[19]D. H. Wilkinson, Philos. Mag. 1, 379 (1956).
[20]R. J. Drachman, Phys. Rev. Lett. 17, 1017 (1966).
[21]T. A. Griffy, Phys. Lett. 21, 693 (1966).
[22]H. Stocker, A. A. Rollefson, and C. P. Browne, Phys. Rev. C 4, 1028 (1971).
[23]S. E. Darden and H. R. Hiddleston, private communication.
[24]J. P. Sokol, Nucl. Instrum. Methods 99, 379 (1972).
[25]Yissum Research Development Company, Hebrew University of Jerusalem, Jerusalem, Israel.
[26]W. Fitz, R. Jahr, and R. Santo, Nucl. Phys. A101, 449 (1967).
[27]C. J. Borkowski and M. K. Kopp, Rev. Sci. Instrum. 39, 1515 (1968).
[28]C. J. Borkowski and M. K. Kopp, IEEE Trans. Nucl. Sci. 17, 340 (1970).
[29]P. L. Jolivette, H. Stocker, and A. F. Hrejsa, Bull. Am. Phys. Soc. 16, 1171 (1971).
[30]H. W. Barz, R. Fülle, D. Netzband, R. Reif, K. Schlott, and J. Slotta, Nucl. Phys. 73, 474 (1965).
[31]J. P. Schiffer, G. C. Morrison, R. H. Siemssen, and B. Zeidman, Phys. Rev. 164, 1274 (1967).
[32]S. Hinds and R. Middleton, Nucl. Phys. 38, 114 (1962).
[33]H. Stocker, Ph.D. thesis, University of Notre Dame, 1972 (unpublished).
[34]T. Lauritsen and F. Ajzenberg-Selove, Nucl. Phys. 78, 1 (1966).
[35]R. H. Bassel, G. R. Satchler, R. M. Drisko, and E. Rost, Phys. Rev. 128, 2693 (1962).
[36]W. Tobocman, *Theory of Direct Nuclear Reactions* (Oxford U. P., London, 1961).
[37]G. R. Satchler, Nucl. Phys. 55, 1 (1964).
[38]P. D. Kunz, University of Colorado, unpublished.
[39]B. A. Watson, R. E. Segel, J. J. Kroepfl, and P. P. Singh, Phys. Rev. 187, 1351 (1969).
[40]H. Enge, *Introduction to Nuclear Physics* (Addison-Wesley, Reading, Mass., 1966), p. 174.
[41]G. T. A. Squier, E. A. McClatchie, A. R. Johnston, R. J. Batten, J. B. A. England, and F. G. Kingston, Nucl. Phys. A119, 369 (1968).
[42]B. Vaucher, J. C. Alder, and C. Joseph, Helv. Phys. Acta 43, 237 (1970).
[43]D. R. Inglis, Rev. Mod. Phys. 25, 390 (1953).
[44]M. G. Mayer and J. H. D. Jensen, *Elementary Theory of Nuclear Shell Structure* (Wiley, New York, 1955), pp. 182–183.
[45]G. Schrank, E. K. Warburton, and W. W. Daehnick, Phys. Rev. 127, 2159 (1962).
[46]K. L. Coop, J. M. Poate, and E. W. Titterton, Aust. J. Phys. 20, 609 (1967).
[47]J. R. Erskine and C. P. Browne, Phys. Rev. 123, 958 (1961).
[48]W. D. Callender and C. P. Browne, Phys. Rev. C 2, 1 (1970).
[49]C. P. Browne and J. R. Erskine, Phys. Rev. 143, 683 (1966).
[50]H. H. Gutbrod, H. Yoshida, and R. Bock, Nucl. Phys. A165, 240 (1971).
[51]M. N. Huberman, M. Kamegai, and G. C. Morrison, Phys. Rev. 129, 791 (1963).
[52]G. C. Morrison, Phys. Rev. Lett. 5, 565 (1960).
[53]G. T. Garvey and J. C. Hiebert, Bull. Am. Phys. Soc. 9, 44 (1964).
[54]K. L. Coop, J. M. Poate, and E. W. Titterton, Nature 213, 587 (1967).
[55]J. R. Duray and C. P. Browne, Phys. Rev. C 1, 776 (1970).
[56]E. A. Kamykowski, private communication.
[57]C. M. Chesterfield and B. M. Spicer, in *Isobaric Spin in Nuclear Physics*, edited by J. D. Fox and D. Robson (Academic, New York, 1966), pp. 734–738.
[58]P. B. Tollefsrud and P. L. Jolivette, Phys. Rev. C 1, 398 (1970).
[59]C. M. Chesterfield and P. D. Parker, Bull. Am. Phys. Soc. 15, 1654 (1970).
[60]J. V. Noble, Phys. Rev. 173, 1034 (1968).
[61]H. Feshbach, in *Nuclear Spectroscopy Part B*, edited by F. Ajzenberg-Selove (Academic, New York, 1960), pp. 625–669.
[62]H. T. Richards and H. V. Smith, Jr., Phys. Rev. Lett. 27, 1735 (1971).
[63]P. L. Jolivette, Ph.D. thesis, University of Wisconsin, 1970 (unpublished).
[64]A. F. Hrejsa and C. P. Browne, Phys. Rev. C 8, 230 (1973).