Semidirect T-Forbidden Reaction $^{12}C(d,\alpha)^{10}B_{0^+,T=1}$*

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The T-forbidden (d,α) reaction on ^{12}C leading to the 0^+, $T=1$ state in ^{10}B has been investigated at deuteron bombarding energies from 13 to 21 MeV. The shape of the angular distributions is practically energy-independent. The angular distributions are characteristic of a direct-reaction mechanism, in agreement with the results obtained by Meyer-Schützmeister, v. Ehrenstein, and Allas for deuteron energies from 11 to 13 MeV. The excitation function shows two pronounced resonances in the range from $E_d=13$ to 15 MeV with peak cross sections of 120 and 90 μb/sr, respectively. The resonances correspond to states in the compound nucleus ^{14}N at $E_x=21.15\pm0.15$ MeV with a width Γ of ≈1.4 MeV, and at $E_x=22.70\pm0.10$ MeV with a width of ≈0.9 MeV. This is the region of the giant electric dipole resonance. From $E_d=15.5$ to 21 MeV, the cross section is small and the excitation function is practically energy-independent. The cross section in the peak of the angular distribution is about 5 μb/sr. Thus the reaction exhibits a contradictory behavior, having both direct- and compound-nucleus features. The reaction mechanism is discussed in terms of a two-step process consisting of a T-violating step and a (d,α)-like reaction. For the T-violating step, we have considered virtual Coulomb excitation and the preferential spin-flip process suggested recently by Noble for deuteron-induced reactions. A consideration of the characteristics and estimated magnitudes of the various effects suggests that the spin-flip process or (virtual) $E1$ Coulomb excitation of the deuteron (polarization of the deuteron in the Coulomb field of the other nucleus) can probably explain the experimental results for $E_d>15.5$ MeV. However, it appears that these processes cannot account for the magnitude and the resonancelike behavior of the cross section at $E_d=13$–15 MeV. A mechanism is suggested which postulates the existence of certain clusterlike, quasibound two-particle–two-hole states in the region of the giant resonance. The existence of such states has been suggested by Gillet, Melkanoff, and Raynal in a study of the fine structure of the giant resonance. The proposed reaction would proceed by an *induced* spin-flip in the deuteron at the corresponding bombarding energies.

I. INTRODUCTION

ISOSPIN-FORBIDDEN (d,α) reactions have been studied experimentally in the past on a number of light self-conjugate nuclei and over a wide range of deuteron bombarding energies.[1,2] The states in the final nucleus are often the 0^+, $T=1$ states which occur at low-excitation energies in the odd self-conjugate nuclei. Closely related are many other reactions including inelastic scattering on self-conjugate nuclei involving deuterons, α particles, and ^6Li particles. The main features of most of the results are essentially understood.[3,4] The reactions proceed via formation of a compound nucleus, and the isospin mixing takes place in the compound system. The amount of isospin mixing depends on the average Coulomb matrix element $\langle H_C\rangle$, the average spacing D_J between states of the same spin and parity but different isospin, and the average width $\langle\Gamma\rangle$ of the overlapping broad compound-nuclear resonances. Estimates of these quantities lead to the conclusion that there should be a severe breakdown of the isospin selection rule for nuclear reactions at intermediate energies. In ^{14}N this region extends from about 8 to about 16 MeV.[3,5] Qualitative agreement exists between the above expectations and the experimental results. Quantitative results concerning the isospin impurities, however, are more difficult to extract because other factors, such as angular momentum conservation rules, affect the cross sections.

In 1966, Meyer-Schützmeister *et al.*[5] reported on the T-violating reaction $^{12}C(d,\alpha)^{10}B$ leading to the 0^+, $T=1$ state in ^{10}B at 1.74-MeV excitation energy. They measured excitation functions and angular distributions up to bombarding energies of $E_d=13$ MeV. At $E_d=11$ MeV the compound contributions to the cross section appear to have practically disappeared. The angular dependence of the differential cross section is very weak, and the magnitude is of the order of 1 μb/sr. Above $E_d=11$ MeV the differential cross section increases sharply in the forward direction, reaching a value of approximately 190 μb/sr in the laboratory system at $\theta_{lab}=20°$ for $E_d=12.5$ MeV. Angular distributions measured at $E_d=12.1$ and 12.5 MeV show very pronounced forward peaks with a maximum near $\theta_{lab}=20°$. No such peak was observed in the backward direction, indicating complete asymmetry about 90°. The observed characteristics of the reaction above $E_d=11$ MeV thus indicate a direct-reaction mechanism.

The present investigation was motivated by the desire to verify this unusual effect and to learn more about its characteristics, particularly at higher bombarding energies. It was hoped that it would be possible to understand the reaction mechanism and to determine the origin of the violation of the isospin selection rule for this particular nuclear reaction.

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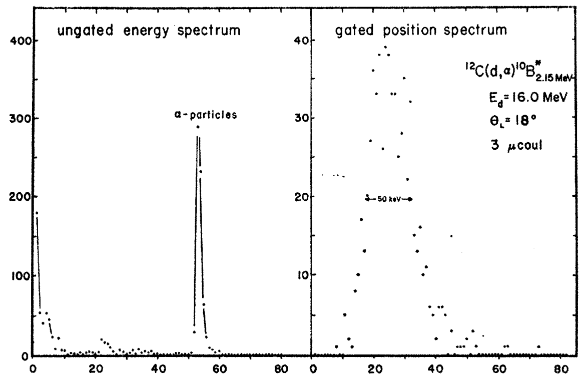

FIG. 1. Ungated energy spectrum and gated position spectrum for the transition to the state at $E_x=2.15$ MeV in ^{10}B.

II. EXPERIMENTAL PROCEDURE

A self-supporting carbon target about 120 $\mu g/cm^2$ in thickness was bombarded with 13–21-MeV deuterons from The University of Michigan 83-in. cyclotron. Most of the data points below 15 MeV, the lowest deuteron energy readily available from the cyclotron, were obtained using an Al absorber between the two beam preparation magnets to degrade the beam energy. While the beam intensity was reduced considerably, the energy resolution was practically unchanged.

The α particles were observed in a position-sensitive detector placed at the image surface of an $n=\frac{1}{2}$ analyzer magnet. The detector was 50-mm wide, and an energy range of typically 250 keV could be covered. The energy resolution obtained in the position spectrum was about 50 keV, mainly due to target thickness. Kinematic line broadening was eliminated by using an effective image surface which shifted by as much as 40 cm over the angular range covered. The energy signal from the detector was used for particle identification. The method is illustrated in Fig. 1, which shows the ungated energy spectrum and the corresponding energy-gated position spectrum for the intense T-allowed transition to the state at 2.15 MeV in ^{10}B. This transition was always used to set the energy discriminator.

The arrangement of analyzer magnet and position-sensitive detector proved to be well suited for measuring the α line of interest despite the small cross sections and the presence of interfering lines from contaminations in the target. A typical position spectrum for the T-forbidden transition is shown in Fig. 2. The line of interest stands out quite clearly even though the cross section is a factor of 1000 less than for the transition shown in Fig. 1. The additional line at the left of Fig. 2 is due to a small oxygen contamination on the target.

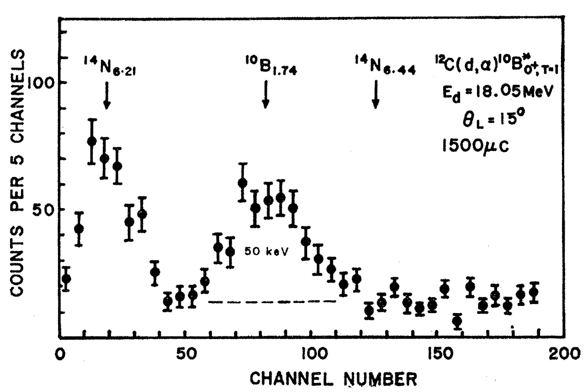

FIG. 2. Position spectrum for the T-forbidden transition to the 0^+, $T=1$ state at $E_x=1.74$ MeV in ^{10}B. An accompanying line from oxygen contaminations on the target is indicated.

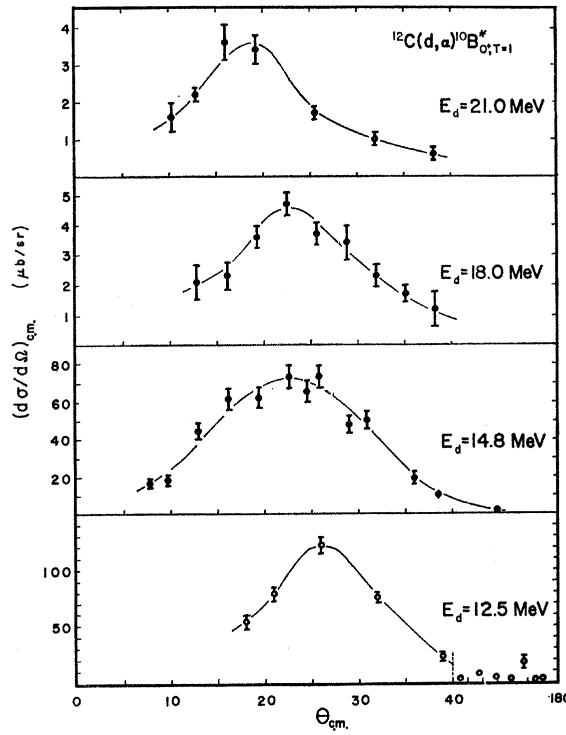

FIG. 3. Angular distributions for the transition to the 0^+, $T=1$ state in ^{10}B at $E_x=1.74$ MeV for deuteron bombarding energies of 21.0, 18.0, 14.8, and 12.5 MeV. The last distribution was taken from Ref. 5.

III. RESULTS

Figure 3 shows three angular distributions which were measured at bombarding energies of 21, 18, and 14.8 MeV (filled circles) together with one of the two angular distributions (lowest curve; open circles) measured by the Argonne group[5] at 12.5 MeV. The shape of the angular distributions remains practically the same over a range of bombarding energies of 9 MeV, while the position of the maximum gradually moves forward with increasing energy. The peak cross sections range from 4 μb/sr at $E_d=21$ MeV to about 120 μb/sr at 12.5 MeV.

The most forward angle which was measured was $\theta_{lab}=6°$ at $E_d=14.8$ MeV. This point was taken to ensure that there is no peak at 0°. Meyer-Schützmeister *et al.*[5] measured the angular distributions at $E_d=12.1$ and 12.5 MeV back to $\theta_{c.m.}=155°$. At both energies there is no backward peak and the forward-to-backward ratio is typically about 10. We have measured one additional forward/backward ratio and obtained at $E_d=15.1$ MeV a value of $\sigma_{c.m.}(24.5°)/\sigma_{c.m.}(155.5°)=3\pm1$. This ratio is obtained if it is assumed that the small peak seen with a single solid-state detector at the backward angle results from the $T=1$ state only. The presence of a contaminating line cannot be excluded, and the above ratio would then increase accordingly.

An excitation function was measured for the transition to the 0^+, $T=1$ state in ^{10}B for deuteron bombarding energies ranging from 13 to 21 MeV. The detector angle θ_{lab} was decreased slightly with increasing bombarding energy to give the maximum differential cross section. The relation between θ_{lab} and E_d was taken from Fig. 3. The angle θ_{lab} decreases from 19° at $E_d=13$ MeV to 13° at $E_d=21$ MeV. Figure 4 shows the result of the measurement (filled circles). Included in the figure are the data measured by the Argonne group[5] at lower bombarding energies and a constant angle of $\theta_{lab}=20°$ (open circles). The five energies above $E_d=11$ MeV at which angular distributions have been measured are indicated by arrows. At energies below $E_d=11$ MeV the angular distributions were found to be essentially symmetric about 90°, indicating that in this region the transition proceeds by a compound process.

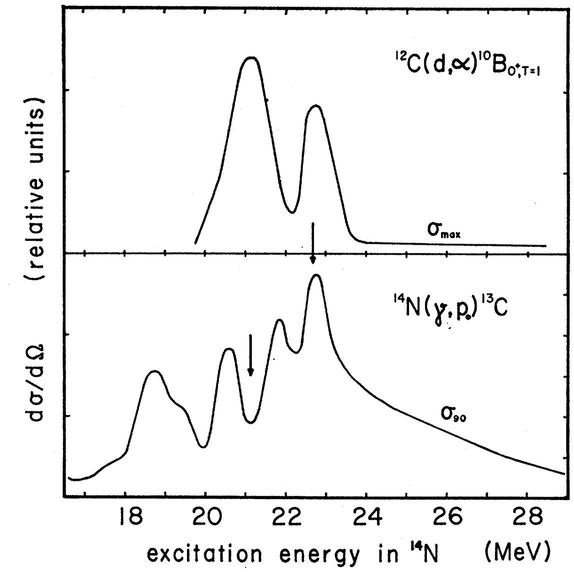

FIG. 5. Comparison between the T-forbidden reaction $^{12}C(d,\alpha)^{10}B_{0^+,T=1}$ with the giant-dipole states in ^{14}N observed in the reaction $^{14}N(\gamma,p_0)^{13}C$. The upper and lower scale differ by a factor of about 2.

IV. DISCUSSION

The effect of interest begins with a threshold near $E_d=11$ MeV. Between $E_d=11$ and 15.5 MeV there are two pronounced peaks in the excitation function with peak cross sections of about 120 and 95 μb/sr, respectively, and with widths of the order of 1 MeV. From $E_d=15.5$ to 21 MeV the cross sections are very small, of the order of 5 μb/sr, and decrease very slowly with energy. All five angular distributions measured between $E_d=11$ and 21 MeV have a very similar shape despite the fact that the absolute values change considerably. The distributions are strongly forward peaked, and the position of the maximum decreases slightly with increasing bombarding energy from 20° to 13°.

Our measurements quite clearly confirm the existence of a T-forbidden (d,α) reaction with the characteristics of a direct reaction. Moreover, the measurements have

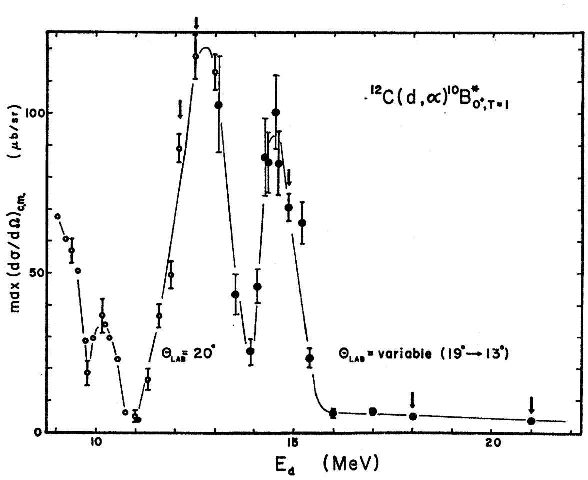

FIG. 4. Excitation function for the transition to the 0^+, $T=1$ state in ^{10}B at $E_x=1.74$ MeV for deuteron bombarding energies from 9 to 21 MeV. The angle θ_{lab} is variable and decreases with increasing bombarding energy from 20° to 13°. The open circles below $E_d=13$ were taken from Ref. 5.

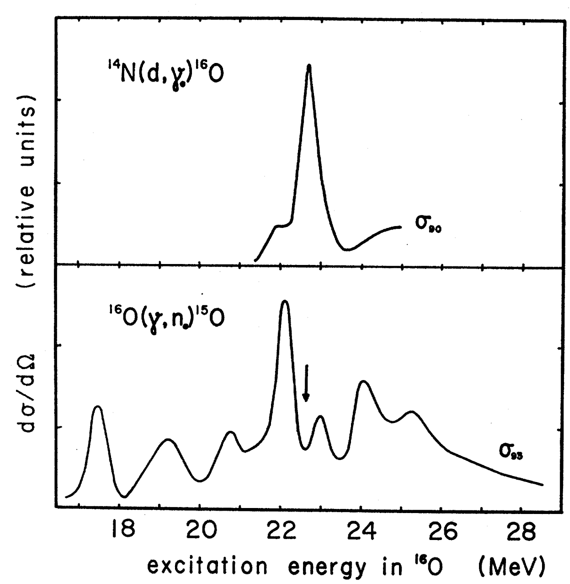

FIG. 6. Comparison between the T-forbidden reaction $^{14}N(d,\gamma_0)^{16}O$ with the giant-dipole states in ^{16}O observed in the reaction $^{16}O(\gamma,n_0)^{15}O$. The upper and lower scale differ by a factor of about 1000.

revealed a very unusual and apparently contradictory behavior. The angular distributions strongly indicate a direct-reaction mechanism while the excitation function indicates a compound-nucleus reaction with two very pronounced resonances. These two observations have to be reconciled. However, one should point out that the lifetime of states having a width of 1 MeV is of the order of 10^{-22} sec. The transit time for a particle in a direct reaction is of the same order of magnitude. A reaction mechanism which exhibits direct- *and* compound-nucleus features is therefore conceivable.

The two peaks in the excitation function correspond to excitation energies in the compound nucleus ^{14}N of 21.15 ± 0.15 and 22.70 ± 0.10 MeV, respectively. The widths are ≈ 1.4 and ≈ 0.9 MeV, respectively. This is the region of the giant-dipole resonance in ^{14}N. Figure 5 shows a combined plot of the cross sections for the T-forbidden (d,α) reaction and the $^{14}\mathrm{N}(\gamma,p_0)^{13}\mathrm{C}$ reaction[6] as a function of the excitation energy in the compound nucleus ^{14}N. The comparison shows that at least the energetically lower line observed in the (d,α) reaction does not coincide with any of the known $J^\pi=(0,1,2)^-$, $T=1$ giant-dipole resonance states in ^{14}N.

A very similar situation has been observed experimentally by Suffert[7] in a different reaction. He observed a pronounced resonance in the reaction $^{14}\mathrm{N}(d,\gamma_0)^{16}\mathrm{O}$ using direct observation of the ground-state γ transition of about 20 MeV. The resonance at $E_d \approx 2.4$ MeV corresponds to an excitation energy in ^{16}O of 22.70 ± 0.05 MeV. The width of the state is ≈ 0.4 MeV. There are also indications for broader lines at ≈ 22.2 and ≈ 24.5 MeV. Figure 6 shows the comparison between the excitation functions for the reactions $^{14}\mathrm{N}(d,\gamma_0)^{16}\mathrm{O}$ [Ref. 7] and $^{16}\mathrm{O}(\gamma,n_0)^{15}\mathrm{O}$ [Ref. 8] plotted as a function of the excitation energy in ^{16}O. The latter reaction, as well as other reactions[7] such as $^{15}\mathrm{N}(p,\gamma_0)^{16}\mathrm{O}$, which have a very similar shape, determine the $J^\pi=1^-$, $T=1$ states of the giant electric dipole resonance in ^{16}O. The resonance seen in the reaction $^{14}\mathrm{N}(d,\gamma)$ does not coincide with any of these states. A level at $E_x=22.8\pm0.1$ MeV in ^{16}O has also been observed in a (γ,p) reaction,[9] presumably by $M1$ excitation. Since the energy is very close to the energy of the state in the $^{14}\mathrm{N}(d,\gamma)$ reaction, the two levels are perhaps identical. Several resonances have been seen in the $^{12}\mathrm{C}(\alpha,\gamma)^{16}\mathrm{O}$ reaction,[10] but none which is near the $^{14}\mathrm{N}(d,\gamma)^{16}\mathrm{O}$ resonance.

The similarity between the observed characteristics of the $^{12}\mathrm{C}(d,\alpha)^{10}\mathrm{B}_{0^+,T=1}$ and $^{14}\mathrm{N}(d,\gamma_0)^{16}\mathrm{O}$ reactions suggests that the two may be related. Both reactions are T-forbidden, they are deuteron-induced, and the target nuclei are self-conjugate. Both reactions lead to resonances at energies in the region of the giant resonance in the compound system but not coinciding with the known giant-resonance states. Therefore the reaction $^{14}\mathrm{N}(d,\gamma)^{16}\mathrm{O}$ and the attempts at an interpretation will be discussed below.

The state at $E_x=22.7$ MeV in ^{16}O has isospin $T=0$ or $T=1$ or a mixture of both. If $T=0$, then the formation of the state is T-allowed, but the subsequent $E1$ or $M1$ γ transitions[7] are forbidden or at least strongly inhibited due to isospin selection rules for γ transitions.[11] If $T=1$, then the formation of the state is T-forbidden, but the subsequent γ transition is not very much affected by T-selection rules. Thus, for all possible combinations of spins, parities, and isospins, i.e., $J^\pi=1^-$ or 1^+, $T=1$ or $T=0$, the reaction is inhibited due to isospin-selection rules, except when there is strong isospin mixing.

Several theoretical publications[12–14] deal with the fine structure of the ^{16}O giant-dipole resonance and/or with the state at $E_x=22.7$ MeV seen by Suffert.[7]

Assuming interference between states with $J^\pi=1^-$ and $T=0$ and $T=1$, respectively, Yoccoz and Jang[12] essentially reproduced the weak asymmetry in the experimental γ-ray angular distribution of the $^{14}\mathrm{N}(d,\gamma)$ reaction.

For $M1$ transitions particle-hole states of the type $(1p)^{-1}(2p)^{+1}$, etc., have essentially no transition strength.[13] Only higher-order corrections lead to a certain magnetic-dipole strength. Such states with $J^\pi=1^+$, $T=1$ have been predicted[13] near 20 and 29 MeV. Two-particle–two-hole states of the type $(1p)^{-2}(1d2s)^{+2}$ with $J^\pi=1^+$ will not contribute to electromagnetic transitions directly.

Gillett *et al.*[14] introduced clusterlike quasibound few-particle–few-hole $J^\pi=1^-$, $T=1$ states which couple to the simple one-particle–one-hole giant-dipole resonance states. The γ transitions to the ground state become possible because of the coupling to the $1p$-$1h$ states. At least three major shell jumps are needed for parity conservation. This means that the $2p$-$2h$ states must have shell-model configurations of the type $(1p)^{-2}(1d2s)^{+1}(1f2p)^{+1}$, which, however, does not exclude the possibility for simple ^{14}N–d-cluster configurations. Such a state at $E_x=22.7$ MeV can indeed explain part of the observed fine structure[14] in the ^{16}O giant electric dipole resonance.

The energetics of the reactions are shown in Fig. 7. The figure includes a resonance in the $^{16}\mathrm{O}+d$ system which is indicated from the preliminary results we

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have obtained for the T-forbidden reaction $^{16}O(d,\alpha)$ $^{14}N_{0^+,T=1}$. Two angular distributions measured near $E_d=15$ MeV exhibit shapes which are practically identical to the ones shown in Fig. 3. The resonance structure is observed at $E_d\approx 15$ MeV.

The reaction $^{14}N(d,\gamma)$ has practically no competition from the (d,α) reaction because the α-particle energy is too small. The reaction has been studied[7] with deuteron energies as low as 0.5 MeV. Therefore, the presence of another state in ^{16}O with similar characteristics below $E_x=21.4$ MeV cannot be excluded. The figure also shows that there is only a limited number of reactions with deuterons in the ingoing or outgoing channel which can be utilized to observe the above resonances. In particular, T-forbidden inelastic deuteron scattering cannot be used.

It is of considerable interest to understand the reaction mechanism for the T-forbidden (d,α) reaction. Small $T=1$ admixtures in the ground states of ^{12}C, the deuteron, and the α particle, as well as $T=0$ admixtures in the 0^+, $T=1$ state of ^{10}B, are likely to exist. Such admixtures, however, cannot account for the observed direct transition, since a one-step process with only a single transferred L value is still parity-forbidden. One must therefore conclude that the reaction proceeds via a two-step process with the formation of an intermediate virtual state. One step may be a process like (virtual) Coulomb excitation which does not conserve isospin. The other step could then be some kind of (d,α) reaction with the pickup of a properly coupled proton-neutron pair or the knockout of an α particle. Several theoretical papers have appeared in the past which are related to the above problems.[2,15–19] Of particular interest is a new T-violating effect in d-induced reactions suggested by Noble.[2,19] The various possibilities for (virtual) Coulomb excitation or de-excitation will be discussed first. Noble's papers and the possible relations to the observed experimental effects will be discussed next.

There are eight possible ways for Coulomb excitation or de-excitation, namely $E1$ and $M1$ transitions within any of the four reaction partners. The eight cases are shown in Table I. In the process (1) to (4) the projectile or the target nucueus are Coulomb-excited by a virtual $E1$ or $M1$ transition. An intermediate excited state in the deuteron or in ^{12}C is formed, and the second step then consists of a (d,α)-like reaction. In processes (5) to (8) the order of the two steps is reversed. The first step consists of a (d,α)-like reaction leading to an intermediate excited state in the α particle or in ^{10}B. The second step consists of virtual $E1$ or $M1$ Coulomb de-

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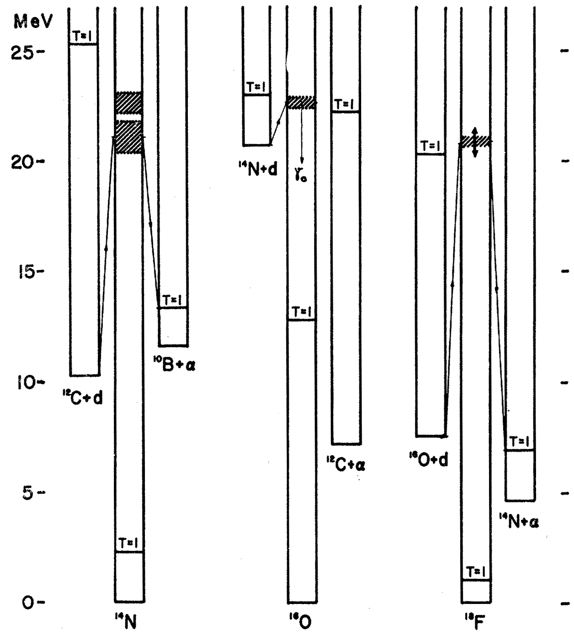

FIG. 7. Energetics of the T-forbidden reactions $^{12}C(d,\alpha)^{10}B$, $^{14}N(d,\gamma)^{16}O$, and $^{16}O(d,\alpha)^{14}N$.

excitation. The angular momentum transfer values L for the (d,α)-like reactions are indicated for all eight cases. It should be noted, however, that only the reactions (2), (4), (6), and (8) have the character of an ordinary (d,α) reaction involving real deuterons and α particles. If the (d,α)-like reaction proceeds via direct pickup of a proton-neutron pair, we have the pickup of a $J=0$ coupled pair φ with $L=0, S=0, T=1$ (singlet deuteron) in the cases (3) and (7) or the pickup of a pair $\tilde{\varphi}$ carrying an orbital angular momentum, i.e., $L=1, S=1, T=1$, in the cases (1) and (5). The situation in cases (3) and (7) is similar to that for a (p,t) reaction. The situation in cases (1) and (5) is more complex.

Only a few of the cases (1) to (8) have been discussed in the literature. The most widely considered mechanism[5,15–17,19] is the $E1$ Coulomb excitation of the deuteron. Detailed calculations have been performed by Drachman[16] and by Griffy.[17] The effect is usually referred to as the polarization of the deuteron in the Coulomb field of the other nucleus. Discussions and/or calculations related to the other effects are rare. The cases (3) ($M1$ of the deuteron), (5) ($E1$ of the α particle), (8) ($M1$ of ^{10}B) have been considered by Clarkson and Griffy,[18] Griffy,[17] Meyer-Schützmeister *et al.*,[5] and Noble,[19] respectively.

Using the adiabatic approximation Drachman[16] has estimated the isospin admixtures in the wave function of the deuteron for process (1). He assumed a finite-size deuteron and a point nucleus with Z protons at a distance x. For the quantity $\alpha(x)$ in the schematic expansion

TABLE I. Possible modes of Coulomb excitation or de-excitation.

^{12}C	+	d	→	$^{12}C^{(*)}$	+	$d^{(*)}$	→	$^{10}B^*$	+	α	Eq.
$0^+, 0$		$1^+, 0$	$E1$ (d)	$0^+, 0$		$1^-, 1$	(d,α) $L=1$	$0^+, 1$		$0^+, 0$	(1)
			$E1$ (^{12}C)	$1^-, 1$		$1^+, 0$	(d,α) $L=1$				(2)
			$M1$ (d)	$0^+, 0$		0^+ or (2^+), 1	(d,α) $L=0$ or (2)				(3)
			$M1$ (^{12}C)	$1^+, 0$		$1^+, 0$	(d,α) $L=0$ and/or 2				(4)
^{12}C	+	d	→	$^{10}B^*$	+	$\alpha^{(*)}$	→	$^{10}B^*$	+	α	
$0^+, 0$		$1^+, 0$	(d,α) $L=1$	$0^+, 1$		$1^-, 1$	$E1$ (α)	$0^+, 1$		$0^+, 0$	(5)
			(d,α) $L=1$	$1^-, 0$		$0^+, 0$	$E1$ (^{10}B)				(6)
			(d,α) $L=0$ or 2	$0^+, 1$		$1^+, 1$	$M1$ (α)				(7)
			(d,α) $L=0$ and/or 2	$1^+, 0$		$0^+, 0$	$M1$ (^{10}B)				(8)

$$\psi(^{12}\mathrm{C},d;x)=\psi(^{12}\mathrm{C})\psi(d)\chi(L=0)+\alpha(x)\psi(^{12}\mathrm{C})\psi(\bar{\varphi})\chi(L=1) \quad (9)$$

(^{12}C is used as an example), he obtained the expression

$$\alpha^2=Z^2G(x)\,, \quad (10)$$

where the function $G(x)$ is given explicitly in analytical form, and Z is the charge of the nucleus causing the Coulomb excitation. The function $G(x)$ depends on the shape and the size of the deuteron. It should be noted at this point that the admixture in the wave function of Eq. (9) can be interpreted as a virtual excitation to an intermediate state. In this sense the admixture in Eq. (9) represents the intermediate state of Eq. (1).

Griffy[17] has made a similar estimate of the $T=1$ admixture based on first-order perturbation theory. He derived the expression

$$\alpha^2=Z^2\left(\frac{e^2\hbar c}{4\pi^2}\right)\frac{\int\sigma(E)dE}{E_x^{\,3}}\left(\frac{1}{x}\right)^4, \quad (11)$$

where $\int\sigma(E)dE$ is the photon absorption cross section integrated over the giant electric dipole resonance and E_x is the excitation energy of the giant resonance. The numerical value for the coefficient is $(e^2\hbar_x)/(4\pi^2)=0.717$ $(\mathrm{MeV})^3(\mathrm{fm})^4(\mathrm{MeV\ mb})^{-1}$.

Griffy[17] applied Eq. (11) to the α particle and the deuteron. Using $\int\sigma(E)dE=7.5$ MeV mb and $E_x=30$ MeV for the α particle gives (x measured in fm)

$$\alpha^2=Z^2\times2.0\times10^{-4}x^{-4}\,,$$
$$\alpha=Z\times1.4\times10^{-2}x^{-2}\,; \quad (12)$$

using $\int\sigma(E)dE=10$ MeV mb and $E_x=5$ MeV for the deuteron[20] gives

$$\alpha^2=Z^2\times5.7\times10^{-2}x^{-4}\,,$$
$$\alpha=Z\times2.4\times10^{-1}x^{-2}\,. \quad (13)$$

The integrated cross sections from the dipole sum rule[21] $\int\sigma(E)dE=60\ ZN/A$ MeV mb would result in values for α^2 which are increased by factors of 8 and 3, respectively.

It is interesting to note that Drachman's[16] and Griffy's[17] expressions agree to within a few percent at larger distances. This is remarkable since the numerical values for the former expression are based on the shape and size of the deuteron while the ones for the latter were obtained from the characteristics of the electric giant-dipole resonance. For $x=10$ fm the estimates differ by only 2%. Agreement to within 20% persists inward to about 5 fm. For $x=3.2$ fm, the nuclear radius for $^{12}C(r_0=1.4$ fm), Griffy's estimate is higher by a factor of about 4.

The relative contributions to α^2 from $E1$ Coulomb excitation of the deuteron, of the α particle, of ^{12}C and of ^{10}B in the reaction $^{12}C(d,\alpha)^{10}B$ can be estimated from Eq. (11). For the deuteron and the α particle the results of Eqs. (12) and (13) can be taken directly. For ^{12}C and ^{10}B we used $E_x=20$ MeV and $\int\sigma(E)dE=90$ and 75 MeV mb, respectively. The latter values represent 50% of the dipole sum rule.[21] The result is that the values of α^2 for the α particle, ^{12}C, and ^{10}B are very small. They are only of the order of 0.5% of the value obtained for the deuteron. The strong reduction follows from the fact that α^2 is proportional to E_x^{-3}. An additional reduction for ^{12}C and ^{10}B follows from the Z^2 factor which is only 1 and 4, respectively, as compared to 36 for the deuteron.

Reliable estimates for the $T=1$ admixtures due to $M1$ Coulomb excitation are more difficult to obtain. It is generally stated[22] that magnetic transitions are much weaker than the corresponding electric transitions. This result is likely to hold also with respect to the processes considered in Eqs. (1) to (8). The $M1$ photodisintegration cross section for the deuteron, for instance, is considerably smaller than the $E1$ photodisintegration cross section. The relative importance of the magnetic transition of Eq. (3) compared to the electric transition of Eq. (1) may, however, be increased due to the fact that the $M1$ excitation function for photodisintegration has its maximum at a lower energy. The characteristics of the T-violating spin-flip effect (discussed below) which was suggested by Noble[19] and of $M1$ Coulomb excitation of the deuteron are

[20] An apparent numerical error for the deuteron in Ref. 17 was pointed out to us by J. Duray (factors of about 8 for α and about 70 for α^2).

[21] A. M. Green, Rept. Progr. Phys. 28, 113 (1965).

[22] K. Alder, A. Bohr, T. Huus, B. Mottelson, and A. Winter, Rev. Mod. Phys. 28, 432 (1956).

similar even though the effects are of completely different origin. Noble[19] states that the spin-flip effect leads to relatively large T violations as compared with a $M1$ transition. Noble[19] also has calculated an intensity ratio of 10^{-4} for $M1$ Coulomb de-excitation of ^{10}B [Eq. (8)] with respect to the spin-flip process.

From the above considerations, we conclude that the predominant effect is the $E1$ Coulomb excitation of the deuteron (polarization of the deuteron). From Eq. (10) and the function $G(x)$ as given by Drachman[16] one calculates a value of $\alpha^2 \approx 0.5\%$ for the $T=1$ admixtures in the deuteron wave function when the deuteron reaches the surface of the ^{12}C nucleus. The differential cross section in forward direction for an unhindered (d,α) reaction[23] at $E_d \approx 15$ MeV is typically $d\sigma/d\Omega = 3$ mb/sr. Multiplying this value by α^2 gives $d\sigma/d\Omega = 15$ μb/sr, which is close to but still somewhat higher than the experimentally observed maximum cross section for the forbidden reaction at bombarding energies from $E_d = 15.5$ to 21 MeV. If the (d,α)-like reaction proceeds through pickup of two nucleons there will be an additional reduction in the cross section. (There is no overlap between two proton-neutron pairs of the type $\tilde{\varphi}$ with $L=1$, $S=1$, $T=1$ and a real α particle unless the α particle is also polarized in a three-step process.) Noble[19] estimates that the intensity of the process would be reduced by another factor of about 10^{+5}. Equation (12) gives an only slightly different estimate. However, the above argument is not necessarily valid. The general characteristics of (d,α) reactions are not well understood. In particular, strong peaks in backward direction are often seen and indicate the presence of exchange effects. It is therefore likely that the α-particle knockout mechanism plays an important role for the understanding of the angular distributions in forward direction. This mechanism leads only to a reduction[24] by a factor of the order of 4, which still leaves us with a differential cross section of about $d\sigma/d\Omega = 4$ μb/sr. The reduction results essentially from the incomplete overlap of $^{10}B_{0^+,T=1}$ with $^8Be_{g.s.} + \tilde{\varphi}$.

We conclude that the $E1$ Coulomb excitation mechanism for the deuteron followed by a (d,α)-like reaction should not be excluded for the interpretation of the small, only slightly energy-dependent cross section of about 4–6 μb/sr measured at bombarding energies higher than $E_d = 15.5$ MeV. The observed angular distributions are reasonable. The adiabaticity parameter ξ for our bombarding energies is very small and the corresponding $E1$ angular distributions[22] are strongly forward peaked with maxima below $\theta = 30°$ and vanishing cross section at $\theta = 0°$. (The $M1$ angular distributions[22] are very similar). The combined angular distributions for the two-step process consisting of Coulomb excitation and the (d,α)-like reaction with $L=1$ would probably preserve some of these characteristics.

On the other hand, the estimated cross section for the above mechanism is definitely too small to account for the observed cross section in the range $E_d = 11$ to 15.5 MeV. Moreover, Coulomb excitation cannot lead to a resonancelike behavior.

Noble[2,19] in two recent publications has suggested a new mechanism which leads to a violation of isospin T in direct- and compound-nucleus reactions involving deuterons. He concludes[19] that this mechanism can explain the experimental results of Meyer-Schützmeister *et al.*[5] (i.e., angular distributions at $E_d = 12.5$ MeV and the excitation function from $E_d = 11$ to 13 MeV), both qualitatively and quantitatively.

The character of the new mechanism is similar to $M1$ Coulomb excitation of the deuteron but of different origin. The long-range Coulomb force destroys the symmetry between the strong nuclear spin-orbit parts of the n-^{12}C and p-^{12}C forces and thus leads to a preferential spin flip. Noble's[2,19] papers include an extensive analysis and study of this effect. In our paper we are only concerned with the aspects related to the direct part of this mechanism.

The question one has to answer is whether or not the effect can explain the magnitude and shape of the excitation function and of the angular distribution. Noble[19] has made an order-of-magnitude estimate of the intensity ratio for the forbidden to allowed differential cross section at 30°. The result is 0.1%, which is practically equal to the estimate obtained for the $E1$ Coulomb excitation of the deuteron. Using again a typical differential cross section for the allowed transitions in forward direction[23] of $d\sigma/d\Omega = 3$ mb/sr we compare the product, which gives $d\sigma/d\Omega = 3$ μb/sr, with the peak differential cross section for the forbidden transition at bombarding energies higher than 15.5 MeV of about 5 μb/sr. We conclude that the effect is strong enough to explain the long tail in the excitation function beyond 15.5 MeV. The experimental energy dependence is reasonable. At higher energies the energy dependence of the spin-flip process is weak. It is determined by the Coulomb asymmetry factor[2,24a] which gives a difference of only a few percent between 16 and 21 MeV. The experimental angular distributions are also reasonable. Noble[19] has derived an approximate expression for the angular distributions. The cross section for $\theta = 0°$ vanishes. From the similarity in the expressions derived for spin flip and for $M1$ Coulomb excitation one would think that the shapes of the angular distributions should be related. Indeed, the angular distributions for the latter[22] bear close resemblance to the experimental distributions. A quantitative comparison

[23] F. Pellegrini, Nucl. Phys. **24**, 372 (1961); T. Yanabu, S. Yamashita, T. Nakamura, K. Takamatsu, A. Masaike, S. Kakigi, D. C. Nguyen, and K. Takimoto, J. Phys. Soc. Japan **18**, 742 (1963).

[24] Calculated from the wave functions of A. N. Bojarkina, Izv. Akad. Nauk. SSSR Ser. Fiz. **28**, 338 (1964).

[24a] *Note added in proof.* J. V. Noble (private communication) has pointed out to us that the major factor may be the energy dependence of the nuclear spin-orbit interaction.

is not possible at this moment because of the complexity of the (d,α) reaction.

The spin-flip process seemingly cannot explain the major contribution to the effect in the range $E_d=11$ to 15.5 MeV. The calculated effect appears to be too weak, and a resonancelike behavior seems not to be a constituent of the mechanism. Interferences with the compound-nucleus part of the effect would seem to be excluded because the angular distributions remain essentially unchanged across the resonance.

In order to understand the effect in the resonance region one would of course like to preserve some of the characteristics of the preferential spin-flip mechanism introduced by Noble.[2,19] We feel that this can perhaps be done by including nuclear-structure aspects. We suggest a hypothesis which is presented in the following paragraph.

Gillet *et al.*[14] have suggested the existence of few-particle–few-hole states in the region of the giant electric dipole resonance. These states have $J^\pi=1^-$, $T=1$. They mix with the ordinary one-particle–one-hole giant-resonance states and contribute to the fine structure of the giant resonance.[14] This mixing results in some $E1$ transition strength to the ground state as observed by Suffert.[7] As pointed out by Gillet *et al.*[14] these states are clusterlike quasibound states. We now suggest that some of these states are based on the cluster configuration of the ^{12}C ground state plus a singlet deuteron φ in a relative $L=1$ motion.[25] In addition we assume a transition between the $L=1$ partial wave of the ^{12}C plus deuteron scattering state on the one hand and the above clusterlike quasibound state on the other hand. The transition is *induced* at deuteron energies which correspond to the cluster state (or states) in the compound system by means of the preferential spin-flip mechanism. This effect would exhibit resonancelike behavior and preserve the features of the original spin-flip mechanism.[2,19] It is not clear, however, whether "direct" angular distributions would still result from that effect. The above hypothesis connects problems and questions related to the understanding of the T-forbidden (d,α) reaction, the T-forbidden (d,γ) reaction,[7] and the fine structure of the giant electric dipole resonance.[14]

[25] Noble (Ref. 2) postulated the existence of similar states in a study of the isospin admixtures in certain discrete states. He predicted states with $L=3$ and $L=1$ characteristics at excitation energies of about 12 to 19 MeV.

More theoretical work is desirable to prove or to disprove the suggested effect of an *induced* spin-flip mechanism with resonances at energies which correspond to certain states in the compound system and to eventually fully understand the observed effects. More experimental work is also desirable to provide more information. As mentioned above, we have started an investigation of the T-forbidden ^{16}O$(d,\alpha)^{14}$N reaction and have observed a similar effect. Other possible reactions which should be studied include the deuteron breakup and the (d,γ) reactions on ^{12}C and ^{16}O.

In summation, our measurements have confirmed the presence of the T-violating reaction $^{12}C(d,\alpha)^{10}$B leading to the 0^+, $T=1$ state in ^{10}B with the characteristics of a direct reaction.[5] The measurements have revealed an apparently contradictory behavior, namely pronounced resonances in the range $E_d=11$ to 15.5 MeV. The resonances occur at energies which correspond to the region of the giant-dipole resonance in the compound nucleus. From $E_d=15.5$ to 21 MeV the effect persists with practically no change in the shape of the angular distribution, but the cross section is very small. The preferential spin-flip mechanism[2,19] and/or $E1$ Coulomb excitation of the deuteron[16,17] (polarization of the deuteron) can explain the weak contributions to the effect at the higher energies. The resonancelike behavior is seemingly not understood. It is suggested that a spin-flip is induced in the deuteron at energies which correspond to certain clusterlike quasibound, two-particle–two-hole states in the compound system. The transition utilizes the $L=1$ partial wave of the ^{12}C plus deuteron scattering state.

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