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Isospin-Forbidden and Allowed $^{12}\text{C}(\text{d},\alpha)^{10}\text{B}$ Cross Sections[†]

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ABSTRACT

We report extensive new data on the isospin-forbidden $^{12}\text{C}(\text{d},\alpha_2)^{10}\text{B}(1.74)$ reaction for $7.19 \text{ MeV} \leq E_d \leq 13.99 \text{ MeV}$. We also report extensive data for the isospin-allowed $^{12}\text{C}(\text{d},\alpha_{0,1,3})^{10}\text{B}$ reactions. All channels exhibit resonant behavior indicative of compound nucleus formation. We find no evidence for appreciable direct or semi-direct contribution to the α_2 cross sections. A partial-wave expansion of the α_2 data fixes J^π for a number of (isospin-mixed) ^{14}N compound nuclear levels. Our data do not support either Noble's proposed ^6Li mechanism or Weller's modification to Noble's proposal.

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I. Introduction

Since the deuteron, the alpha particle, and the ground state of ^{12}C all have zero isospin ($T = 0$), and the second excited state of ^{10}B (1.74 MeV, $J^\pi = 0^+$) has $T = 1$, the reaction $^{12}\text{C}(d, \alpha_2) ^{10}\text{B}(1.74)$ is isospin-forbidden. Thus, if the isospin quantum number is strictly conserved in nuclear reactions, the yield for this reaction is zero. Substantial reaction cross sections for this and other isospin-forbidden reactions occur,¹⁻¹² and are generally attributed to isospin mixing by Coulomb forces in the compound nuclear states. However, Meyer-Schützmeister, von Ehrenstein, and Allas² and Jänecke, Yang, Polichar, and Gray^{3,12} suggest their $^{12}\text{C}(d, \alpha_2) ^{10}\text{B}$ data require a direct mechanism. Also Jänecke et al.^{5,12} believe their $^{16}\text{O}(d, \alpha_1) ^{14}\text{N}(2.31)$ data imply a direct or semi-direct mechanism. Since direct nuclear reactions should conserve isospin (the collision times are so short that the Coulomb forces will not appreciably mix states of different isospin¹³⁻¹⁵), the proposal that isospin non-conservation occurs via a direct mechanism requires careful examination. We therefore investigate the reported direct behavior of the $^{12}\text{C}(d, \alpha_2) ^{10}\text{B}$ reaction for $11.3 \text{ MeV} \leq E_d \leq 14.0 \text{ MeV}$.^{2,3} In addition, we repeat and extend the previous measurements for $7.2 \text{ MeV} \leq E_d \leq 11.3 \text{ MeV}$ to study in greater detail the compound mechanism reported for this region² and to search for mirror cluster states in ^{14}N similar to those found in ^8Be .¹⁶ (Such mirror cluster states can explain relatively large isospin-mixing observed in a reaction of this type.)

The direct mechanisms proposed^{2,3,17-20} to explain the previous $^{12}\text{C}(d, \alpha_2) ^{10}\text{B}$ results generally do not permit cross sections of the magnitude

which the data require and in particular do not account for the two resonant like maxima which Ref. 3 reports in a forward angle excitation function (Fig. 4 of Ref. 3). Noble proposes²¹ a second order direct process to explain the two resonant maxima. He suggests that the incoming deuteron picks up an α particle from the ^{12}C target, forming ^6Li in one of its two (supposedly isospin-mixed) $J^\pi = 2^+$ states ($E_x = 4.57 \text{ MeV}$, $T = 0$ and $E_x = 5.36 \text{ MeV}$, $T = 1$), leaving a residual nucleus, ^8Be . The $^6\text{Li}^*(2^+)$ then decays into a singlet deuteron, d , and an α particle. The ^8Be nucleus absorbs the d , forming $^{10}\text{B}(1.74, J^\pi = 0^+, T = 1)$ and leaving the detected α particle. The two resonant like peaks result from E_d assuming values suitable for forming the 2^+ states in ^6Li , which constitute a $T = 0$, $T = 1$ doublet. The existence of bands of cluster states near two-particle breakup thresholds²² plus the possibility of appreciable isospin-mixing in the $^6\text{Li}^*(2^+)$ states lends credibility to this ad hoc mechanism.

Spin and parity restrictions for the $0^+ + 1^+ \rightarrow 0^+ + 0^+$ case hinder the $^{12}\text{C}(d, \alpha_2)^{10}\text{B}$ reaction independent of isospin conservation.²³ However, these restrictions allow us to use the partial-wave analysis developed by Jolivet and Richards²⁴ to determine unambiguously the J^π of a single isolated state of the intermediate nucleus, ^{14}N . The analysis is similar to that used for the $^{14}\text{N}(\alpha, \alpha_1)^{14}\text{N}(2.31)$ and $^{16}\text{O}(d, \alpha_1)^{14}\text{N}(2.31)$ reactions.^{7,11,24}

II. Experimental Procedure

Deuterons (d) from an EN tandem Van de Graaff accelerator bombard a gaseous methane (CH_4) target of thickness $\leq 2 \text{ keV}$ in a differentially-

pumped gas scattering chamber. The experimental arrangements are the same as in Ref. 7 except for the following modifications. A 1.0 to 2.0 μA d^+ beam with angular divergence of $\pm 14'$ passes through the scattering chamber. An array of 8-13 Si surface barrier solid-state detectors records the scattered α particles. We adjust the depletion depths of the solid-state detectors so that the pulse-heights of the competing (d,p) and (d,d) reactions are smaller than that of any α -particle group of interest. The detector collimating slits have angular acceptances ranging from $\pm 1.53^\circ$ to $\pm 2.15^\circ$. In general, each datum point represents the collection of 6000 μC of charge at a methane target gas pressure of 15 Torr.

Since the (d, α) reactions on ^{13}C and ^{16}O may result in contaminant peaks in the spectral region of interest, the ^{13}C and ^{16}O content in the methane target gas and the cross sections for the $^{13}\text{C}(\text{d},\alpha)^{11}\text{B}$ and $^{16}\text{O}(\text{d},\alpha)^{14}\text{N}$ reactions are of interest. Our directly measured $^{13}\text{C}/^{12}\text{C}$ isotopic ratio for the methane target gas is consistent²⁵ with the natural abundance value of 0.0112. At certain angles and energies the α_2 group from the $^{12}\text{C}(\text{d},\alpha_2)^{10}\text{B}$ reaction may overlap alpha-particle groups from the $^{13}\text{C}(\text{d},\alpha_1)^{11}\text{B}$ (i = 7-11) reactions. No cross section data exist for the $^{13}\text{C}(\text{d},\alpha_1)^{11}\text{B}$ (i = 7-11) reactions, but typical values for the (d, α_{1-3}) reaction on ^{13}C are 400 $\mu\text{b}/\text{sr}$.^{26,27} Using 400 $\mu\text{b}/\text{sr}$ as the maximum cross section for the $^{13}\text{C}(\text{d},\alpha_1)^{11}\text{B}$ (i = 7-11) reactions, the maximum possible contamination of our $^{12}\text{C}(\text{d},\alpha)^{10}\text{B}$ data due to ^{13}C is 4 $\mu\text{b}/\text{sr}$. Ref. 2 reports no α -particle group in their magnetic spectrograph spectra for $9 \text{ MeV} \leq E_d \leq 13 \text{ MeV}$ which corresponds to the $^{13}\text{C}(\text{d},\alpha_1)^{11}\text{B}$ (i = 7-11) reactions. We also do not observe any of these groups. The manufacturer states that the oxygen content of our methane target gas²⁸ is

$^{16}\text{O}/^{12}\text{C} \approx 10^{-4}$. Jobst²⁹ observes 5 mb/sr as a maximum cross section for any of the $^{16}\text{O}(\text{d}, \alpha_i)^{14}\text{N}$ ($i = 6-11$) reactions ($8 \text{ MeV} \leq E_d \leq 9 \text{ MeV}$). If we assume the same maximum as an upper limit for the $^{16}\text{O}(\text{d}, \alpha_i)^{14}\text{N}$ ($i = 6-18$) reactions, then the ^{16}O contaminant contributes at most only 0.5 $\mu\text{b/sr}$ to our $^{12}\text{C}(\text{d}, \alpha)^{10}\text{B}$ data at the overlap angles and energies. In fact, at no energy or angle do we observe any $^{16}\text{O}(\text{d}, \alpha_i)^{14}\text{N}$ groups.

Figure 1 shows typical α -particle spectra. The α_2 group has low yield (typically 1% of the nearby isospin-allowed groups); thus, accurate estimation of the background is important. (The background in the region of the α_2 group can arise from beam collimator slit-edge scattering, pile-up between the elastic protons or deuterons and the α groups, and detector electronic noise). We use a non-linear least squares computer program³⁰ to fit the background (assumed to be exponential) and the α_2 and α_3 peaks (assumed to be gaussian). In fitting the spectra, the position of the α_2 group is fixed, the width of the α_2 group is set equal to that of the α_3 group, and the program varies the other gaussian peak parameters (width of α_3 , position of α_3 , and areas of α_2 and α_3) and the background until chi square is minimized.

Since the cross sections for the $^{12}\text{C}(\text{d}, \alpha_2)^{10}\text{B}$ reaction are quite small, statistical uncertainties are the largest source of error for this channel. A detailed error analysis³¹ indicates that the systematic uncertainties in all the cross section measurements may be as large as 2% with possibly another 2% random error in addition to the statistical errors. We note that the cross sections at all angles may be up to 0.4% low due to beam heating effects, and that the cross section at the four most forward angles (20° c.m., 26° c.m., 33° c.m., and 45° c.m.) may be up to 1% low due to pile-up effects. The uncer-

tainty in the absolute energy scale is placed at ± 15 keV. Reference 31 contains a detailed description of the experimental procedure.

III. Results

The differential cross section measurements consist of excitation functions taken simultaneously at 8-13 angles. Figures 2-5 exhibit the excitation functions for the isospin-forbidden α_2 channel. Figures 6-9, Figs. 10-13, and Figs. 14-17 show the (simultaneously recorded) excitation functions for the isospin-allowed α_0 , α_1 , and α_3 channels. The deuteron bombarding energy, E_d , varies in 40 keV steps for $7.19 \text{ MeV} \leq E_d \leq 13.67 \text{ MeV}$ and 80 keV steps for $13.67 \text{ MeV} \leq E_d \leq 13.99 \text{ MeV}$. Because of the narrow resonance in the α_2 channel at $E_d = 9.61 \text{ MeV}$, E_d varies in 20 keV steps for $9.51 \text{ MeV} \leq E_d \leq 9.71 \text{ MeV}$. E_d in Figs. 2-17 is corrected for energy loss to the center of the target (the correction is ~ 10 keV).

A few selected angular distributions for the isospin-forbidden α_2 channel are shown in Figs. 18-20. We obtain total cross sections for the α_0 , α_1 , and α_3 channels by fitting the angular distributions with a Legendre polynomial expansion. The total cross sections for the α_2 channel are a result of the partial-wave analysis (see below). The total cross sections for the α_0 , α_1 , α_2 , and α_3 channels are shown in Fig. 21.

At many angles and energies the differential cross sections shown in Figs. 6-17 overlap previous $^{12}\text{C}(d, \alpha_{0,1,3})^{10}\text{B}$ measurements.^{2,32,33} Table I shows a comparison of the differential cross section scale reported here and the scales reported in Refs. 2, 32, and 33. The agreement between

the present scale and those of Refs. 32 and 33 is good. The discrepancy of approximately 40% between the present scale and that of Ref. 2 is a factor of two more than the reported systematic errors. Perhaps the discrepancy arises from the presence of narrow resonances in the $^{12}\text{C}(p,p_0)^{12}\text{C}$ excitation functions³⁴ near the energies, $E_p = 8.15$ MeV and 9.27 MeV, that Ref. 2 used for target thickness measurements. These resonances are not reported in Ref. 35, which contains the $^{12}\text{C}(p,p_0)^{12}\text{C}$ cross sections Ref. 2 used for normalizing their differential cross sections.

At some angles and energies the cross sections shown in Figs. 2-5 overlap the $^{12}\text{C}(d,\alpha_2)^{10}\text{B}$ data of Ref. 2 (but do not overlap the data of Ref. 3). In general, the agreement between the present data and that of Ref. 2 is good (when the cross section scale of Ref. 2 is corrected for the 40% discrepancy discussed above). However, there are places where the two sets of α_2 data disagree even after the cross section scale of Ref. 2 has been corrected. For example, for $9 \text{ MeV} \leq E_d \leq 10 \text{ MeV}$, $\theta_{\text{lab}} = 120^\circ$ ($\theta_{\text{c.m.}} \approx 137^\circ$), the present measurements are $\sim 100\%$ higher than those of Ref. 2. Also, at $E_d = 12.5 \text{ MeV}$, $150^\circ \leq \theta_{\text{c.m.}} \leq 160^\circ$, the present measurements are $\sim 400\%$ higher than those of Ref. 2. The sources of these discrepancies are unknown.

IV. Discussion of Results

Violations of the isospin selection rule may result from isospin impurities in the incoming channel, in the intermediate state, and/or the outgoing channel. Since the $T=1$ impurities of the ^{12}C ground state, the ^4He ground state, and the ^{10}B second excited state are es-

estimated³⁶ to be 0.1%, 0.001%, and 0.07% respectively, and the T=1 impurity of the deuteron is expected to be negligible, direct reactions should introduce isospin impurities of only a few tenths of a percent for $^{12}\text{C}(d, \alpha_2)^{10}\text{B}$. Large isospin impurities in the intermediate states can result from the Coulomb force mixing nearby continuum states of the same J^π but differing isospin.¹⁴ Qualitatively, the cross sections

due to direct effects vary slowly with energy, whereas those due to compound effects exhibit resonances which correspond to isospin-mixed intermediate states.

Single-step direct mechanisms with a single ℓ transfer are also spin-parity forbidden for $^{12}\text{C}(d, \alpha_2)^{10}\text{B}$.³⁷ Multiple-step direct mechanisms are needed to account for non-zero cross sections. Estimates of the isospin impurities introduced by multi-step direct mechanisms are on the order of a tenth of a percent.^{17,19} Cross sections due to multi-step direct mechanisms are, in general, expected to be slowly varying with energy, although broad resonant structure is predicted by mechanisms such as Noble's ^6Li mechanism.²¹

Our data indicate that the source of isospin-mixing in the $^{12}\text{C}(d, \alpha_2)^{10}\text{B}$ reaction for $7.2 \text{ MeV} \leq E_d \leq 14.0 \text{ MeV}$ is ^{14}N intermediate states. The ratios of the isospin-forbidden α_2 total cross sections to the isospin-allowed α_0 , α_1 , and α_3 total cross sections (Fig. 21) are $\sim 1\%$, an order of magnitude larger than predicted by direct or multi-step direct mechanisms. More significantly, relatively narrow resonances are present in the α_2 excitation functions (Figs. 2-5). These narrow resonances imply long lived ^{14}N intermediate states as the source of the isospin-impurity. The angular distributions for the

α_2 channel (a few of which are shown in Figs. 18-20; also Fig. 1, Ref. 38 and Fig. 3, Ref. 39) vary in symmetry about 90° c.m., sometimes being symmetric, but often being asymmetric in either the forward or backward directions. Below we will interpret the variation in fore-aft symmetry of the α_2 angular distributions in terms of interference effects between overlapping ^{14}N intermediate states of opposite parity. We confirm the conclusion² that for $^{12}\text{C}(d, \alpha_2)^{10}\text{B}$ a compound mechanism dominates the region $E_d \leq 11.3$ MeV; we disagree with the conclusion^{2,3} that a direct mechanism dominates the region $11.3 \text{ MeV} \leq E_d \leq 14$ MeV. (In the region of disagreement between our interpretation and that of Refs. 2 and 3, our data are much more extensive.)

The α_0 , α_1 , and α_3 excitation functions exhibit (weak) fluctuations indicating that compound processes contribute to these channels. This is consistent with the findings of Klabes, Baldeweg, and Stiller³² that intermediate states are important for $9 \text{ MeV} < E_d < 14$ MeV. Individual resonances occur in these channels (e.g., the resonance(s) in the α_0 and α_1 channels near $E_d = 12.5$ MeV, Figs. 6-13, and the resonance in the α_3 channel near $E_d = 11.5$ MeV, Figs. 14-17) further verifying the importance of ^{14}N intermediate states.

V. Analysis

Since our data indicate that the isospin impurity in the $^{12}\text{C}(d, \alpha_2)^{10}\text{B}$ reaction is introduced by ^{14}N intermediate states, the object of our analysis is to explain the α_2 cross sections with a suitable set of (isospin-mixed) ^{14}N states. In order to eliminate interference effects between overlapping, isospin-mixed ^{14}N states of differing J^π , we

parametrize our α_2 data (Figs. 2-5) with S-matrix elements (S_ℓ 's) according to the prescription of Jolivet and Richards:²⁴

$$d\sigma/d\Omega = (\lambda^2/12) |\sum_\ell (2\ell+1) [\ell(\ell+1)]^{-1/2} S_\ell dP_\ell(\cos\theta)/d\theta|^2 \quad (1)$$

References 7, 24, and 31 contain a detailed discussion of the fitting procedure. We interpret a resonance in the ℓ^{th} partial wave as a ^{14}N level with $J^\pi = \ell(-1)^\ell$.

There exist $2^{\ell_{\text{max}}-2}$ degenerate sets of S_ℓ 's (each set is called a "solution") which give identical fits to the angular distributions.²⁴ The amplitude of the $\ell_{\text{max}}^{\text{th}}$ partial wave is unique -- the degeneracy is in the other $(\ell_{\text{max}}-1)$ partial waves. The highest ℓ_{max} that we require to obtain acceptable fits to our data is 5; thus, we have eight degenerate sets of S_ℓ 's from which to choose the "physical" solution. One simplification arises, namely the $2^{\ell_{\text{max}}-2}$ solutions tend to pair into $2^{\ell_{\text{max}}-3}$ solutions which differ substantially in amplitude of the partial waves. Table II illustrates this pairing. The eight ambiguous solutions "pair" into only four solutions with substantially different S-matrix elements. Thus, we are left with four solutions from which to choose the "physical" solution.

The criterion that we use to choose the "physical" solution from the four degenerate solutions is based on the prediction¹⁵ that isospin conservation in reactions involving intermediate states of increasing excitation is spin dependent, being reestablished first for the lowest spin states. For $20.7 \text{ MeV} \leq E_x \leq 22.2 \text{ MeV}$ ($12.2 \text{ MeV} \leq E_d \leq 14.0 \text{ MeV}$), we find that two of the four degenerate solutions have, on the average,

substantially smaller $|S_1|$ and $|S_2|$. The two preferred solutions are sets I, II and III, IV of Table II (although set VII, VIII in Table II has essentially the same $|S_1|$ and $|S_2|$ as set I, II, set I, II has lower $|S_1|$ and $|S_2|$ over most of the range $20.7 \text{ MeV} \leq E_x \leq 22.2 \text{ MeV}$). On the basis of the above criterion we believe that one of these two preferred solutions corresponds to the "physical" solution (we have no reason for choosing between them). The two preferred solutions are identical for $8.0 \text{ MeV} \leq E_d \leq 9.4 \text{ MeV}$, and are qualitatively similar for $9.4 \text{ MeV} \leq E_d \leq 14 \text{ MeV}$. One of the two preferred solution, solution set I, II of Table II, is shown in Fig. 2 of Ref. 38.

We point out that 1) it is difficult to guarantee that one stays with the same solution as the energy changes⁴⁰ and 2) our criterion for choosing the "physical" solution differs from Jolivette's criterion⁴⁰ (Jolivette's criterion is to choose the solution which implies the fewest resonant states). Such a criterion may not pick one of our two preferred solutions as the physical solution. Indeed, Jolivette finds that the "physical" solution for his $^{16}\text{O}(d, \alpha_1)^{14}\text{N}(2.31)$ data implies large $|S_1|$ and $|S_2|$ for high ^{18}F excitation energy.⁴¹ The giant dipole resonance may enhance the contribution from 1^- states at these energies.

The bulk of the ^{14}N level assignments from our $^{12}\text{C}(d, \alpha_2)^{10}\text{B}$ data (shown in Table III) are obtained from a visual inspection of the two preferred solutions discussed above. We demand consistency between the two preferred solutions in making a level assignment. Despite the above warnings, we believe the J^π assignments are unambiguous. There is, of course, no ambiguity if the resonance occurs in the $\ell_{\text{max}}^{\text{th}}$ partial wave or if, for $\ell < \ell_{\text{max}}$, all solutions show the resonance (this is

generally true for $\ell \geq 3$). For those resonances where $\ell < \ell_{\max}$, the locations and widths implied by the different solutions often vary, causing these quantities to be more uncertain than for $\ell = \ell_{\max}$. In addition to these problems, interference effects in a single partial wave (interference effects between overlapping ^{14}N states of the same J^π) are large. The presence of these interference effects is confirmed by the preliminary results of fitting the partial waves in Fig. 2 of Ref. 38 with a multilevel expansion.⁴² An extensive reexamination of our partial wave analysis to insure continuity of solutions and to check our choice of a physical solution (by using Jolivet's criteria) is underway. The results of the multilevel fitting of the partial waves of the physical solution will be presented in a future publication.

The ^{14}N level assignment at $E_x = 16.9$ MeV, shown as (5^-) in Table III occurs in an energy region ($7.67 \text{ MeV} \leq E_d \leq 7.91 \text{ MeV}$) where we cannot successfully parametrize the α_2 data with $\ell_{\max} = 4$ and in which we have too few angles to allow $\ell_{\max} = 5$. While this result only implies that the ^{14}N resonance at $E_x = 16.9$ MeV (indicated by the sharp peak in the 20° excitation function at $E_d = 7.8$ MeV, Fig. 2) has natural spin-parity $\geq 5^-$, the qualitative behavior of this peak as a function of angle suggests $J^\pi = 5^-$. For $E_d < 7.67$ MeV the data are successfully parametrized with $\ell_{\max} = 4$ and imply uniquely that the peak at $E_d \approx 7.6$ MeV at $\theta_{\text{c.m.}} \approx 20^\circ$ and 34° (Fig. 2) arises from a 4^+ level in ^{14}N at $E_x = 16.8$ MeV.

The α_2 channel is sensitive only to those ^{14}N states that have natural parity and that are isospin-mixed ($T = 0$ states with $T = 1$ impurity or vice-versa). Hence we expect to observe only a very few of the existing ^{14}N states via the α_2 channel. Indeed, we find that

fifteen ^{14}N states (Table III) qualitatively account for most of the α_2 cross sections in the 6 MeV excitation region studied. The average ^{14}N level spacing, D , as observed via the α_2 channel, is $D \sim 400$ keV. The average half-width of these levels, Γ , is $\Gamma \sim 400$ keV. Thus, $\Gamma \sim D$, and the average ^{14}N level spacing, as observed in the α_2 channel, is intermediate to the region of individual, isolated resonances where $\Gamma \ll D$ and the statistical region where $\Gamma \gg D$. In this intermediate region, unlike the individual resonance region, each angular distribution is not required to be symmetric about 90° c.m. Since positive parity states and negative parity states are about equal in number in the α_2 channel, as often as not overlapping states in the α_2 channel have opposite parity. If interference between such overlapping states of opposite parity occurs, asymmetric angular distributions result. Asymmetries in the angular distributions are observed (Figs. 18-20, also Fig. 1 of Ref. 38). These asymmetries (sometimes forward peaking, sometimes backward peaking) persist for energy intervals up to four times the average half-width (Fig. 3 of Ref. 38). Apparently the relative phases between the ^{14}N levels involved have values which produce these intervals of asymmetry.

From the ratio, $R (= \sigma_T(\alpha_2)/\sigma_T(\alpha_1))$, of the isospin-forbidden to isospin-allowed total cross sections (Fig. 21) and the inhibition factor, I.F., which corrects R for angular momentum, parity, and penetrability restrictions (I.F. is obtained from a Hauser-Feshbach calculation for $E_x = 19.7 \text{ MeV}^2$), we estimate a lower limit to the isospin impurity, $\beta^2 (= R/(R+\text{I.F.}))$, of some individual levels observed in the α_2 channel. The isospin impurity estimate is a lower limit because we assume that only compound processes contribute to the isospin-allowed channels.

The estimate is typically $\sim 10\%$, e.g., the estimate for the 4^+ level at $E_x = 17.2$ MeV is $\beta^2 \approx 9\%$.³¹ An additional correction for the relative densities of $T = 0$ and $T = 1$ states allows us to estimate the lower limit for the average isospin impurity, $\langle \beta^2 \rangle (= 4/3 [-1 + \sqrt{1 + R/I.F.}])$, of all the ^{14}N resonances that we observe in the α_2 channel. This lower limit is 4% .³¹

One may hope to determine the isospin composition (predominantly $T = 0$ with some $T = 1$ impurity or vice versa) of the ^{14}N levels that we assign from the α_2 data by comparing them with $T = 0$ and $T = 1$ ^{14}N levels and with $T = 1$ ^{14}C and ^{14}O levels for the corresponding ^{14}N excitation energy range. This approach is not successful since either spin and parity information is generally lacking for the ^{14}C , ^{14}N and ^{14}O levels in the region of interest or the reported levels have unnatural spin and parity⁴³ (only natural parity levels may decay via the α_2 channel).

The 1^- level that we observe in the α_2 channel at $E_x = 20.1$ MeV may account for the difference in the $^{14}\text{N}(\gamma, p)^{13}\text{C}$ and $^{14}\text{N}(\gamma, n)^{13}\text{N}$ cross sections observed near $E_x = 20$ MeV.^{44,45} When the differential cross sections for these two reactions are plotted on the same graph (Fig. 2 of Ref. 45), they differ substantially in the region of $E_x = 20$ MeV. This behavior we expect if the (γ, p) and (γ, n) reactions proceed via a ^{14}N state which is primarily $T = 1$ with some $T = 0$ impurity.⁴⁶ (0^- , 1^- , and 2^- ^{14}N states can be excited via the E1 giant dipole resonance.) We tentatively identify this isospin-mixed ^{14}N state as the 1^- level we observe at 20.1 MeV.

We find some evidence for grouping of ^{14}N states of the

same J^π for $3 \leq J \leq 5$. Levels which appear to group are the two 3^- levels at $E_x = 18.2$ MeV and 18.4 MeV; the 4^+ levels at $E_x = 16.8$ MeV, 17.2 MeV, 18.1 MeV, and 18.8 MeV; a possible cluster of 4^+ levels near $E_x \approx 21.3$ MeV; and the two 5^- levels at 20.8 MeV and 21.7 MeV.

One explanation for grouping of two or more isospin-mixed levels of the same J^π is that the levels have appreciable mirror configurations (similar to the famous ^8Be 2^+ levels at 16.6 MeV and 16.9 MeV¹⁶).

Another explanation for grouping is that two or more unrelated states of the same J^π and different isospin accidentally overlap, their isospins being mixed by the Coulomb force. For such unrelated states, the incoming and outgoing partial widths are also unrelated. Hence it is possible that one (or more) of the states does not have an observable cross section. This might explain why some resonances in the partial waves are isolated; e.g., the 5^- resonance at $E_x = 18.50$ MeV (Fig. 2 of Ref. 38).

Noble's ^6Li mechanism²¹ fails to explain our α_2 data.³⁹ The failure of Noble's ^6Li mechanism to explain the "fine" structure reported in Ref. 39 led Weller⁴⁷ to modify the ^6Li mechanism by coupling the $^6\text{Li}^*$ and ^8Be "intermediate" nuclei to a state of definite angular momentum, L . If $L \neq 0$, multiplets result. In particular, if $L = 3$, then intermediate states of $J^\pi = 1^-, 3^-,$ and 5^- result with a center of gravity near $E_x = 20.8$ MeV. Our analysis indicates six ^{14}N levels in the region where Weller's model predicts only three. This, coupled with the fact that there appears to be no a priori reason to choose only $L = 3$ for the $^8\text{Be} + ^6\text{Li}^*$ cluster indicates to us that evidence supporting Weller's model is still lacking. Indeed, recent measurements indicate the intensity of the isospin-mixing of the $^6\text{Li}^*$ 2^+ states ($0.008^{+0.60}_{-0.008}$ from Ref. 48, ≤ 0.005 from Ref. 49) is small, perhaps small enough to make isospin-mixing mechanisms involving them unimportant.⁴⁹

VI. Conclusions

We conclude that for $7.2 \text{ MeV} \leq E_d \leq 14.0 \text{ MeV}$ isospin impurities are introduced into the $^{12}\text{C}(d, \alpha_2)^{10}\text{B}$ reaction by a relatively few isospin-mixed ^{14}N intermediate states. In agreement with measurements on other isospin-violating reactions,^{6,7,8,9,10,11} we see no evidence for significant contributions from direct or semi-direct reaction processes.

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TABLE I
Comparison of $^{12}\text{C}(\text{d}, \alpha_{0,1,3})^{10}\text{B}$ differential
cross section scales.

Ref.	Reported systematic errors	$\frac{(\text{d}\sigma/\text{d}\Omega)_{\text{Ref.}} - (\text{d}\sigma/\text{d}\Omega)_{\text{Present}}}{(\text{d}\sigma/\text{d}\Omega)_{\text{Present}}}$
2	20%	- 0.4 ^a
32	20 - 25%	+ .15 ^a
33	16%	+ .07 ^b
Present work	2%	---

^a From graphs in this reference.

^b From cross sections supplied by the authors of this reference.

TABLE II

"Paired" degenerate sets of S-matrix elements for $^{12}\text{C}(\text{d}, \alpha_2)^{10}\text{B}$. These eight degenerate solution sets are obtained at $E_d = 12.43$ MeV, where $\ell_{\text{max}} = 5$. The S-matrix elements (S_ℓ) are parametrized according to $S_\ell = \rho_\ell e^{i\phi_\ell}$, with $\phi_{\ell_{\text{max}}} \equiv 0$. Note that each solution set on the left is almost identical to the solution set in the corresponding position on the right. For the physical reasons discussed in the text, we choose the two "paired" solution sets I, II and III, IV as candidates for the "physical" solution (we have no basis for choosing between the two preferred solutions). Solution set I, II is shown in Fig. 2 of Ref. 38.

Solution Set	ℓ	ρ_ℓ	ϕ_ℓ (radians)	Solution Set	ℓ	ρ_ℓ	ϕ_ℓ (radians)
I	1	.0102	5.848	II	1	.0110	5.842
	2	.0176	0.919		2	.0176	0.874
	3	.0166	0.078		3	.0170	0.053
	4	.0334	1.442		4	.0332	1.441
	5	.0198	0.000		5	.0198	0.000
III	1	.0065	4.839	IV	1	.0072	4.783
	2	.0047	1.399		2	.0038	1.465
	3	.0405	6.081		3	.0404	6.071
	4	.0154	4.997		4	.0156	4.992
	5	.0198	0.000		5	.0198	0.000
V	1	.0230	6.165	VI	1	.0225	6.144
	2	.0034	3.450		2	.0042	3.546
	3	.0290	5.955		3	.0288	5.938
	4	.0265	4.875		4	.0269	4.874
	5	.0198	0.000		5	.0198	0.000
VII	1	.0119	4.087	VIII	1	.0122	4.153
	2	.0166	0.998		2	.0162	0.954
	3	.0331	0.002		3	.0333	6.274
	4	.0221	1.375		4	.0219	1.373
	5	.0198	0.000		5	.0198	0.000

TABLE III

^{14}N levels implied by the present α data and our partial-wave analysis. Parentheses around level parameter assignments indicate uncertainty in the enclosed quantity. Resonant energies and widths are approximate only. (See text for a discussion of ambiguous solution problems.)

E_d (MeV)	E_x (MeV)	J^π	$\Gamma_{c.m.}$ (keV)
7.6	16.8	4^+	~ 300
7.8	16.9	(5^-)	~ 100
8.1	17.2	4^+	~ 300
9.1	18.1	$(1^-, 2^+)$	(~ 300)
9.2	18.1	4^+	~ 600
9.3	18.2	3^-	(~ 400)
9.5	18.4	3^-	(~ 300)
9.61	18.50	5^-	~ 60
10.0	18.8	4^+	(~ 400)
11.5	20.1	1^-	(~ 500)
12.3	20.8	5^-	~ 600
12.3	20.8	$(3^-, 4^+)$	(~ 500)
12.9	21.3	4^+	$(\sim 1000)^a$
13.1	21.5	3^-	(~ 500)
13.4	21.7	5^-	~ 200

^a May be more than one 4^+ level.

FIGURE CAPTIONS

- Fig. 1. Sample spectra for the $^{12}\text{C}(d,\alpha_1)^{10}\text{B}(i)$ reaction. The α -particle groups are labeled by the corresponding final state in ^{10}B . The isospin-forbidden group is $^{10}\text{B}(2)$.
- Fig. 2. $^{12}\text{C}(d,\alpha_2)^{10}\text{B}(1.74)$ cross sections (c.m.) versus laboratory deuteron energy (E_d) measured simultaneously at several fixed laboratory angles. The corresponding $\theta_{\text{c.m.}}$ is largest at the lowest E_d . The error bars represent only the statistical errors. The top scale gives the corresponding excitation energy (E_x) in ^{14}N .
- Fig. 3. Similar to Fig. 2 except different angles.
- Fig. 4. Similar to Fig. 2 except different angles.
- Fig. 5. Similar to Fig. 2 except different angles.
- Fig. 6. $^{12}\text{C}(d,\alpha_0)^{10}\text{B}(\text{g.s.})$ cross sections (c.m.) vs. laboratory deuteron energy (E_d) measured simultaneously at several fixed laboratory angles. The corresponding $\theta_{\text{c.m.}}$ is largest at the lowest E_d . The statistical errors are comparable to the size of the data points.
- Fig. 7. Similar to Fig. 6 except different angles.
- Fig. 8. Similar to Fig. 6 except different angles.
- Fig. 9. Similar to Fig. 6 except different angles.
- Fig. 10. $^{12}\text{C}(d,\alpha_1)^{10}\text{B}(0.717)$ cross sections (c.m.) vs. laboratory deuteron energy (E_d) measured simultaneously at several fixed laboratory angles. The corresponding $\theta_{\text{c.m.}}$ is largest at the lowest E_d . The statistical errors are comparable to the size of the data points.
- Fig. 11. Similar to Fig. 10 except different angles.
- Fig. 12. Similar to Fig. 10 except different angles.

FIGURE CAPTIONS (Cont'd)

- Fig. 13. Similar to Fig. 10 except different angles.
- Fig. 14. $^{12}\text{C}(d, \alpha_3) ^{10}\text{B}(2.15)$ cross sections (c.m.) vs. laboratory deuteron energy (E_d) measured simultaneously at several fixed laboratory angles. The corresponding $0_{\text{c.m.}}$ is largest at the lowest E_d . The statistical errors are comparable to the size of the data points.
- Fig. 15. Similar to Fig. 14 except different angles.
- Fig. 16. Similar to Fig. 14 except different angles.
- Fig. 17. Similar to Fig. 14 except different angles.
- Fig. 18. Some selected angular distributions for the $^{12}\text{C}(d, \alpha_2) ^{10}\text{B}(1.74)$ reaction. The solid line is the partial wave fit to the data. Ordinary spin-parity restrictions require $d\sigma/d\Omega$ to vanish at 0° and 180° (see Refs. 6 and 24). Confidence levels (C.L.; the probability that another measurement would result in a larger χ^2) between 0.10 and 0.90 are acceptable.
- Fig. 19. Similar to Fig. 18 except different energies.
- Fig. 20. Similar to Fig. 18 except different energies.
- Fig. 21. Total cross sections for the $^{12}\text{C}(d, \alpha_{0-3}) ^{10}\text{B}$ reactions as a function of deuteron bombarding energy. The total cross sections for the α_0 , α_1 , and α_3 groups result from fitting the angular distributions with a Legendre polynomial expansion. The total cross sections for the α_2 group come from the partial-wave analysis of the angular distributions:

$$\sigma_T(\alpha_2) = (\pi\lambda^2/3) \sum_{\ell} (2\ell+1) S_{\ell}^2.$$

The top scale gives the corresponding excitation energy, E_x , in ^{14}N .

Fig. 1

Fig. 2

Fig. 3

Fig. 4

Fig. 5

Fig. 6

Fig. 7

Fig. 8

Fig. 9

E_d (MeV)

Fig. 10

Fig. 11

Fig. 12

Fig. 13

Fig. 14

Fig. 15

Fig. 16

Fig. 17

Fig. 18

Fig. 19

Fig. 20

Fig. 21