Isospin Nonconservation in the Reaction $^{12}C(d, \alpha_2)^{10}B(1.74, T = 1)$†

D. von Ehrenstein
Argonne National Laboratory, Argonne, Illinois 60439 and Northern Illinois University, DeKalb, Illinois 60115

and

L. Meyer-Schützmeister, J. E. Monahan, A. Richter,* and J. C. Stoltzfus‡
Argonne National Laboratory, Argonne, Illinois 60439
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The isospin-forbidden reaction $^{12}C(d,\alpha_2)^{10}B(1.74, T=1)$ was investigated for $E_d = 14.0$ to 17.0 MeV. Several full angular distributions were obtained and the excitation function from $E_d = 16.0$ to 17.0 MeV was measured at $\theta_{lab} = 152°$. In the light of these new data, it is clearly not sufficient to interpret the reaction in terms of simple compound-nucleus formation, as seemed to be indicated in previous investigations.

Isospin nonconservation in nuclear reactions that proceed through compound-nucleus formation has been understood for a long time in terms of the mixing of levels with different isospin.[1] Recent (d,α) reaction data on light nuclei seem to imply[2,3] that isospin nonconservation can occur also in direct or semidirect reactions. In a number of papers,[4,5] Noble developed several theoretical interpretations for such a direct or semidirect reaction mechanism. More specifically, his proposed model[5] in which the isospin mixing was assumed to occur via the formation of an intermediary cluster of excited $^6Li^*(2^+; T = 0, 1)$ attracted considerable interest. However, these direct and semidirect models are unable to provide any quantitative explanation of some unexpected experimental results from the reaction $^{12}C(d,\alpha_2)^{10}B^*(1.74\ \text{MeV}; T = 1)$. These results include two full angular distributions[3] at $E_d = 12.1$ and 12.5 MeV, which were strongly forward peaked, and an excitation curve measured by Jänecke, Yang, Polichar, and Gray[6] at forward angles up to 21.0 MeV, which exhibited two resonancelike enhancements of the cross section at about 12.8 and 14.6 MeV. More recently, Smith and Richards[7,8] obtained very extensive data on the same $^{12}C(d,\alpha_2)^{10}B$ reaction, including many full angular distributions for energies up to $E_d =$ 14.0 MeV. These authors state that their data are consistent with a simple compound-nucleus interpretation of the reaction. The angular distributions were fitted by a partial-wave calculation, and the asymmetries about 90° were reproduced by assuming an interference between levels of different parity; at $E_d \gtrsim 12$ MeV, they found predominantly $J^\pi = 4^+$ levels interfering with 5^- levels. Almost all of the angular distributions[8] considered for this interpretation show a pronounced asymmetry about 90°, and above $E_d = 12.0$ MeV this asymmetry is almost always a strong enhancement of the differential cross section at forward angles (σ_{max} at $\theta_{c.m.} \approx 25°$).

Since the distributions of compound-nucleus levels of opposite parity are expected to be very nearly statistically independent, asymmetries in the angular distribution that result from interference of opposite-parity states should tend to average to zero for energy intervals that contain many such levels. This conclusion is independent of whether the levels are observed as individual levels or as Ericson fluctuations. The 2-MeV energy interval from 12.0 to 14.0 MeV in Smith's data[8] may indeed be too small to produce the expected symmetry by averaging the angular distributions (e.g., averaging his angular distributions from 9.0 to 10.0 MeV would produce a strong enhancement at backward angles). Therefore we set out to measure full angular distributions at and above $E_d = 14.0$ MeV with particular emphasis on the backward angles, which previously had been investigated[6] only at one single angle at 15.1 MeV.

The Argonne tandem beam was used to obtain angular distributions, mostly between $\theta_{lab} = 20°$ and 152°, at incident deuteron energies $E_d = 14.0$, 14.4, 14.8, 15.4, 16.0, and 17.0 MeV. Additional data have been accumulated at $\theta_{lab} = 152°$ from $E_d = 16.1$ to 16.8 MeV, mostly in steps of 100 keV. The target was a self-supporting natural-carbon foil 20 $\mu g/cm^2$ thick and inclined 45° to the beam direction. The outgoing α particles were detected in Ilford K-1 plates placed in the focal plane of the broad-range Enge split-pole spectrograph.[9] Appropriate underdevelopment of the plates suppressed the unwanted deuteron tracks while the α-particle tracks remained clearly visible. The

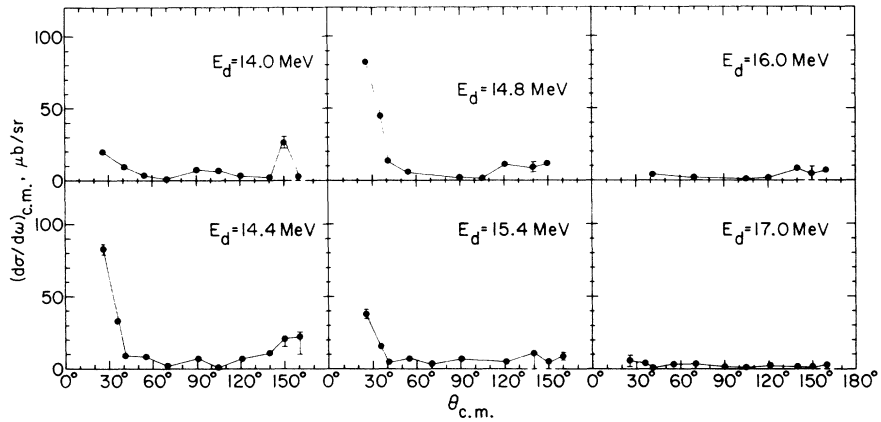

FIG. 1. Experimental angular distributions in the center-of-mass system. The lines connecting the data points are guides for the eye. The error bars include the statistical errors and, in addition, some typical estimated experimental uncertainties (sometimes due to insufficiently resolved contaminant peaks). The absolute errors are estimated to be ±20%.

exposures ranged from 300 to 1200 μC; the solid angle was selected to be 2×10^{-3} sr. The typical instrumental linewidth observed was less than 20 keV, which was mostly due to the target thickness. With this resolution, the contaminant peaks arising from isospin-allowed $O^{16}(d,\alpha)N^{14}$ transitions could be separated from the α groups of interest in most cases.

The results of our measurements appear in Figs. 1 and 2. These show that the cross section at forward angles is enhanced in the angular distributions taken around the resonance,[6] namely at $E_d = 14.4$, 14.8, and 15.4 MeV. In addition, no indication for an increase in the cross section at backward angles was found in the region $E_d = 16.0$ to 17.0 MeV, as can be seen from the excitation function (Fig. 2).

In summary, the angular distributions for the

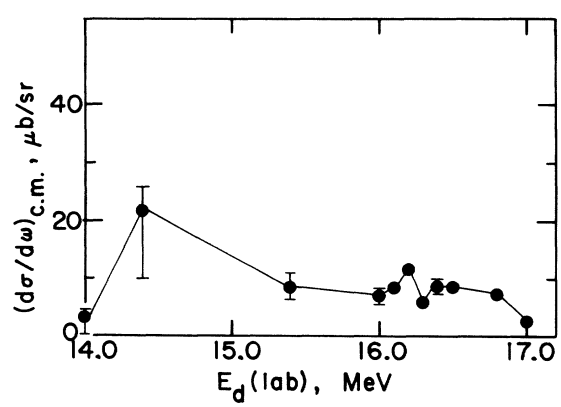

FIG. 2. Differential cross sections in the center-of-mass system at $\theta_{c.m.} \approx 160°$. The line connecting the data points is only a guide for the eye. The errors are as discussed in the caption of Fig. 1.

reaction $^{12}C(d,\alpha_2)^{10}B(1.74\text{ MeV}; T=1)$ show a pronounced enhancement (up to a factor 5) at forward angles within the incident deuteron-energy interval $E_d = 12.0$ to 17.0 MeV. The excitation functions,[6-8] particularly at forward angles, show resonancelike structure.

How can these experimental facts be interpreted? As pointed out previously,[7] a compound-nucleus calculation can indeed reproduce angular distributions that are asymmetric about 90° by assuming interference between pairs of levels with different parity. However, to reproduce the observed asymmetry (in particular, the constructive interference at forward angles that persists over an energy interval that seems to contain several levels) requires unusual restrictions on the distribution and relative phases of these levels. In fact, one of the simplest pictures of the compound-nucleus spectrum that is qualitatively compatible with these data consists of a sequence of nearly degenerate pairs of levels of opposite parity, the levels of each pair having very nearly the same total width. Over the energy interval considered, at least four such "doublets" would be necessary to explain the observed angular distributions. Furthermore, no isolated level could contribute significantly to the reaction over this interval since this would cause a sign change in the interference as the deuteron energy is increased across the resonance. Although the level distribution described above is not defined uniquely by the data, it seems obvious that an unusual correlation between the distributions of levels of opposite parity is necessary to explain the data.

The isospin-nonconserving character of this reaction obviously acts as a selector for particular compound levels that normally are masked by contributions from other levels. For example, penetrability calculations indicate that according to the dynamic criterion,[1] levels with $J<3$ decay too fast and cannot participate in isospin mixing. On the other hand, level-density calculations[10] indicate that levels with $J>6$ (especially those with $T=1$) may occur too infrequently to play a major role in the present reaction. Consequently, compound-nucleus levels with $J=4$ and $J=5$ are the most probable ones involved, as was found out by Smith and Richards[7] in fitting their experimental angular distributions. The average spacings for these levels are sufficiently large that an interpretation of these resonances in terms of Ericson fluctuations seems unlikely; this is contrary to the results[11] of the reaction $^{28}Si(d,\alpha_1)^{26}Al^*(0.23, T=1)$. In addition, an interpretation in terms of Ericson fluctuations would meet with the same type of difficulties that are described above in terms of individual levels. Obviously, the observed nonconservation of isospin must occur either in the entrance or exit channels or in the ^{14}N compound nucleus. None of the proposed channel effects, such as the direct or semidirect mechanisms mentioned above, are in agreement with the present data.

Even if it is assumed that isospin mixing occurs in the compound-nucleus region of configuration space, it remains to explain the peculiar nature of the compound "states" that contribute to this reaction. In this context, it may be of interest to investigate further the ideas presented by Weller[12] in regard to the excited-core-threshold-state model of Baz and Manko.[13] As indicated above, however, an adequate explanation of the isospin-nonconserving reaction $^{12}C(d,\alpha_2)^{10}B(1.74, T=1)$ for deuteron energies between 12 and 17 MeV must incorporate the strong correlation between states of opposite parity (or some other mechanism) sufficient to duplicate the observed angular distributions. In particular, any model of the interaction should predict, in addition to the resonancelike structure in the excitation function, the predominantly forward peaking in the angular distribution of the isospin-nonconserving reaction that does not average out over an interval $\Delta E_d \gtrsim 5$ MeV. In the light of the additional new data presented in the present paper, it is clear that the simple compound-nucleus interpretation is insufficient in itself to explain this reaction.

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*Permanent address: Max-Planck-Institut für Kernphysik, Heidelberg, Germany. Work done while on leave of absence at Argonne National Laboratory.

‡Permanent address: Physics Department, Beloit College, Beloit, Wis. 53511.

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