Isospin Nonconservation in the Reactions $^{16}O(d, \alpha)^{14}N^{*}_{0^+, T=1}$ and $^{12}C(d, \alpha)^{10}B^{*}_{0^+, T=1}$

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The isospin-nonconserving (d, α) reactions on ^{16}O and ^{12}C leading to the 0^+, $T=1$ states at $E_x = 2.31$ MeV in ^{14}N and $E_x = 1.74$ MeV in ^{10}B have been studied in the energy intervals of $E_d = 14.0$ to 18.1 MeV and 26.2 to 29.5 MeV, respectively. Two resonances were observed in the excitation function for the reaction on ^{16}O at $E_d = 14.4$ and 15.0 MeV followed by a weak tail with little energy dependence. This behavior is similar to that observed earlier for the reaction on ^{12}C in the same energy region. The results for ^{12}C at the higher bombarding energies, in conjunction with arguments related to the properties of highly excited states, appear to favor a direct- or semidirect-reaction mechanism. Consistent with the observed facts are virtual $E1$ Coulomb excitation of the deuteron or the preferential spin-flip process suggested by Noble. No evidence was found for the two-step process involving isospin-mixed intermediate states, which was also suggested by Noble.

I. INTRODUCTION

Interest in isospin-nonconserving (d, α) reactions has centered in recent years on the possibility of contributions from direct- or semidirect- (two-step) reaction mechanisms. Meyer-Schützmeister, von Ehrenstein, and Allas[1] observed a pronounced increase in the forward-angle cross section near $E_d = 11$ MeV in the reaction $^{12}C(d,\alpha)^{10}B^*$ leading to the 0^+, $T=1$ state at $E_x = 1.74$ MeV. Two angular distributions measured at $E_d = 12.1$ and 12.5 MeV were strongly forward peaked, which suggested a direct- or semidirect-reaction mechanism. Jänecke *et al.*[2] extended these measurements from 13 MeV up to 21 MeV and established two broad resonance-like structures in the forward-angle excitation function near $E_d = 12.7$ and 14.5 MeV, followed from about $E_d = 15.5$ MeV on, by a weak and essentially energy-independent tail of about 5 μb/sr. Angular distributions measured from $\theta_{lab} = 6$ to 40° remained practically unchanged over a range of bombarding energies of about 10 MeV, which again suggested a direct- or semidirect-reaction mechanism, since compound-nucleus reactions, particularly those involving interfering resonances, generally do not have these characteristics.

Several direct- or semidirect-reaction mechanisms were suggested to explain the data, namely, (i) a preferential spin-flip mechanism in the deuteron[3,4] due to a combination of the nuclear spin-orbit and the long-range Coulomb force, (ii) virtual $E1$ Coulomb excitation of the deuteron[5,2] (polarization of the deuteron in the Coulomb field of the target nucleus), and (iii) a two-step process consisting of a $(d, {}^6Li)$ pick-up reaction followed by a $({}^6Li, \alpha)$ stripping reaction.[6] Here, the ^{6}Li is in one of two isospin-mixed excited 2^+ states. Processes (i) and (ii) were invoked[2] to explain the data at bombarding energies above about 16 MeV, while process (iii) was invoked[6] to explain the resonance-like structures near and below 15 MeV. However, more recently two experiments were reported[7,8] which seem to contradict at least the assumed process (iii). Smith and Richards[7] remeasured in greater detail the lower of the two broad resonances observed near $E_d = 12.7$ MeV in the reaction $^{12}C(d, \alpha)^{10}B^*(1.74$ MeV) and found that it consists of at least three overlapping resonances. The angular distributions show strong $l=4$ components, and a partial-wave analysis indicated a dominance of $l=4$ and $l=5$ partial waves from nearby 4^+ and 5^- states in the compound system. (See also Weller[9] and Smith and Richards.[10])

Richter *et al.*[8] investigated the isospin-nonconserving reaction $^{28}Si(d, \alpha)^{26}Al^*(0.23$ MeV) from $E_d = 12$ to 17 MeV. They observed Ericson fluctuations due to compound-nucleus interference effects and there was no indication of structure which might be attributed to the above process (iii).

The present experiment[11] was undertaken as an extension of the measurements of Jobst, Messelt, and Richards[12] and Jolivette and Richards[13] on the reaction on ^{16}O into the region where the above processes might become important, and secondly as an extension of the various measurements on ^{12}C into a much higher-energy region. The region from about $E_d = 26$ to 30 MeV was chosen for a particular reason. If Noble's two-step process[6] involving isospin-mixed excited states in ^{6}Li does indeed contribute to the reaction, one might expect a similar behavior at higher bombarding energies when the known isospin-mixed 2^+ states in ^{8}Be are involved. A two-step reaction of the type $^{12}C + d \rightarrow {}^8Be^*(16.63\text{-}16.93\ \text{MeV}) + {}^6Li(\text{g.s.}) \rightarrow {}^{10}B^*(1.74\ \text{MeV}) + \alpha$, which has a threshold near $E_d = 26$ MeV, is a natural extension of the mechanism proposed by Noble[6] to explain the resonance-like behavior between $E_d = 12$ and 15 MeV. The only difference is that the strongly isospin-mixed 2^+ states in ^{8}Be are invoked rather than those in ^{6}Li.

II. EXPERIMENTAL PROCEDURE AND RESULTS

A Mylar target of about 550-μg/cm^2 (about 4 μm) thickness and a self-supporting carbon target about 125 μg/cm^2 in thickness were bombarded with deuterons from the University of Michigan 83-in. cyclotron. While only $\frac{1}{3}$ of the Mylar target material (clear Mylar without additives) is oxygen, the remainder being primarily carbon, the reactions on carbon do not interfer with the reaction of interest. The beam current for the Mylar target had to be kept below about 30 nA to reduce target decomposition. A monitor counter was always used for normalization. The α particles were observed in a position-sensitive detector at the image surface of an $n = \frac{1}{2}$ analyzer magnet (see Ref. 2). A few points at backward angles were measured with a solid-state detector in the scattering chamber, since such measurements cannot at present conveniently be done with the magnetic spectrograph.

Figure 1 shows an excitation function for the reaction ^{16}O(d, α)^{14}N*(2.31 MeV) at deuteron bombarding energies from 14.0 to 18.1 MeV. The laboratory angle was kept constant at $\theta_{lab} = 17°$ ($\theta_{c.m.} \approx 20.1°$). Three energies at which angular distributions were measured are indicated by arrows. Figure 2 shows the three angular distributions from about $\theta_{c.m.} = 11$ to 47° measured at $E_d = 14.6$, 15.0, and 15.8 MeV.

The excitation function shows two pronounced resonances at $E_d = 14.35$ and 14.95 MeV, with peak differential cross sections of about 28 and 43 μb/sr, respectively. The two peaks correspond to excitation energies in the compound nucleus ^{18}F of about 20.29 ± 0.07 and 20.82 ± 0.10 MeV, and widths of about 300 and 550 keV, respectively. The differential cross section above $E_d = 15.5$ MeV is about 8 μb/sr and its energy dependence is very weak. There is the possibility of broad structures near $E_d \approx 16.1$ MeV ($E_x \approx 21.9$ MeV) and $E_d \approx 17.6$ MeV ($E_x \approx 23.3$ MeV), but one has to keep in mind that the error bars represent only the statistical uncertainties of the measurements. The data are therefore essentially consistent with a constant cross section.

The angular distributions measured at the three energies, namely, in the minimum between the two peaks and at and above the higher peak, are very similar except for their magnitudes. The position of the maximum in the angular distributions appears to move outward slightly with increasing energy.

Figure 3 shows an excitation function for the reaction ^{12}C(d, α)^{10}B*(1.74 MeV) for deuteron bombarding energies from $E_d = 26.1$ to 29.6 MeV, taken at $\theta_{lab} = 15°$ ($\theta_{c.m.} \approx 19.1°$). Also shown is an angular distribution from about $\theta_{c.m.} = 8$ to 32°, measured at $E_d = 29.1$ MeV. The filled square points

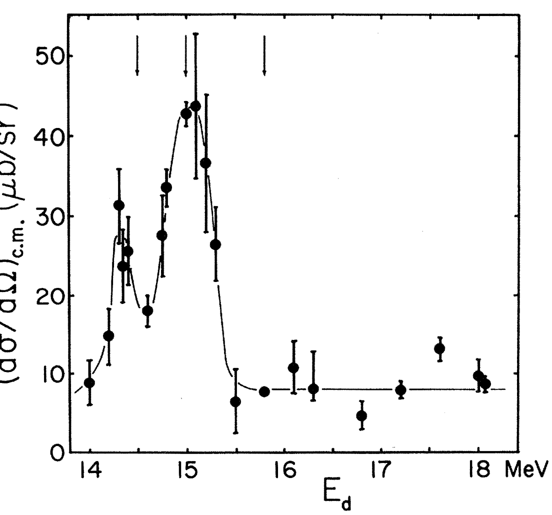

FIG. 1. Excitation function for the isospin-nonconserving reaction ^{16}O(d, α)^{14}N* (2.31 MeV) measured at $\theta_{lab} = 17°$ ($\theta_{c.m.} \approx 20.1°$) for deuteron bombarding energies from $E_d = 14.0$ to 18.1 MeV. The line is drawn to guide the eye.

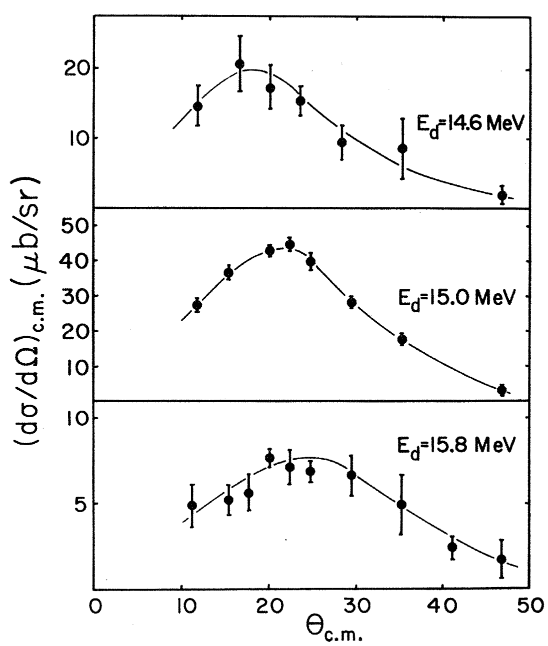

FIG. 2. Angular distributions for the isospin-nonconserving reaction ^{16}O(d, α)^{14}N* (2.31 MeV) measured at $E_d = 14.6$, 15.0, and 15.8 MeV. The lines are drawn to guide the eye.

were measured at $\theta_{c.m.} = 165.4$ and $168.9°$.

The excitation function exhibits only little structure and is essentially consistent with a constant cross section. There are no indications of resonance-like structures attributable to the semidirect process $^{12}C + d \to {}^{8}Be^{*}(16.63\text{-}16.93\ \mathrm{MeV}) + {}^{6}Li(g.s.) \to {}^{10}B^{*}(1.74\ \mathrm{MeV}) + \alpha$. It is worth noting that the differential cross section of about 7 μb/sr is practically equal to that observed earlier[2] at bombarding energies from $E_d = 16$ to 21 MeV. The angular distribution measured at $E_d = 29.1$ MeV has a peak of about 8 μb/sr near $\theta_{c.m.} = 16°$. Two backward-angle measurements gave no detectable strength for the isospin-nonconserving transition and an upper limit of about 3 μb/sr can be placed on the cross section.

III. DISCUSSION

The shape of the angular distributions at forward angles obtained for the isospin-nonconserving (d, α) reaction on oxygen changes very little over the resonances and beyond. This behavior is very similar to that observed earlier[2,7] in the corresponding reaction on carbon. The process involving intermediate ^{6}Li states suggested by Noble[6] cannot be ruled out yet, but the most likely interpretation is that given by Smith and Richards[7] who showed that the lower of the two broad resonances in the isospin-nonconserving reaction on carbon can be explained as a compound-nucleus resonance dominated by $l = 4$ partial waves, with some $l = 5$ admixtures, from 4^+ (and 5^-) states in the compound nucleus. The shape of the measured angular distributions for the oxygen reaction again would suggest high partial waves and therefore high-spin states in the compound nucleus. It is clear, however, that a definite confirmation of a compound-nucleus mechanism for the two resonances can only come from additional measurements, particularly at backward angles. The same holds true for the higher of the two resonances in the reaction on carbon. It should be noted that recently Weller[9] has suggested that the two broad resonances seen in the isospin-nonconserving reaction on carbon (and oxygen) might come from excited core-threshold states[14] based on the cluster configurations $^{8}Be + {}^{6}Li^{*}$ (and $^{12}C + {}^{6}Li^{*}$).

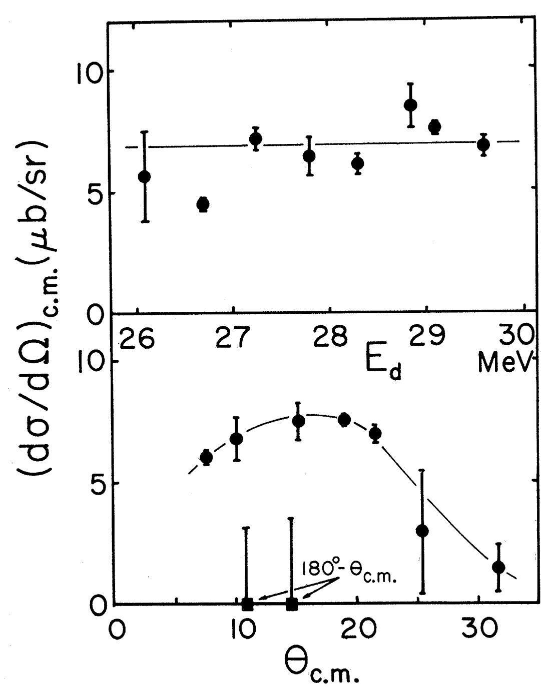

FIG. 3. Excitation function for the isospin-nonconserving reaction $^{12}C(d, \alpha)^{10}B^{*}$ (1.74 MeV) measured at $\theta_{lab} = 15°$ ($\theta_{c.m.} \approx 19.1°$) for deuteron bombarding energies from $E_d = 26.1$ to 29.6 MeV and angular distribution measured at 29.1 MeV. The two backward-angle points (filled squares) were measured at $\theta_{c.m.} = 165.4$ and $169.1°$. The lines are drawn to guide the eye.

Whether the reaction mechanism for bombarding energies beyond $E_d = 16$ MeV in the reactions on both oxygen and carbon is of a direct or a compound-nucleus nature is still an open question. We will give arguments below which seem to favor a direct or semidirect mechanism at least for the reaction on carbon at bombarding energies from $E_d = 26$ to 30 MeV. However, no evidence was found in this energy interval for the special semidirect two-step process suggested by Noble[6] involving isospin-mixed intermediate states.

All the observed characteristics of the reaction on carbon at bombarding energies above $E_d = 16$ MeV are compatible with two semidirect-reaction mechanisms. These are virtual $E1$ Coulomb excitation of the deuteron (polarization of the deuteron in the Coulomb field of the target nucleus[5,2] and Noble's preferential spin-flip effect.[3,4] Estimates for the strength and the angular dependence of these effects have been made earlier[2] and yielded forward-angle differential cross sections of the order of 5 μb/sr, and angular distributions resembling those of $E1$ or $M1$ Coulomb excitation.

There are additional arguments which can be given in favor of a direct- or semidirect-reaction mechanism at the higher bombarding energies. These arguments also provide some explanation for the observed compound-nucleus features of the isospin-nonconserving reactions on carbon (Refs. 1, 2, and 7), oxygen (Refs. 12, 13, and this paper; see also Tollefsrud and Jolivette[15]), and silicon (Ref. 8), at bombarding energies which are not too low. The important factor is the average level width Γ as was pointed out by Müller.[16] Müller predicted two basically different extreme types of behavior in isospin-nonconserving compound-nucleus reactions, with Ericson fluctuations at one extreme and at the other resonances mostly due to pairs of selected states.

Ericson fluctuations will occur if $\Gamma \gg D$, where D is the average level spacing. Strong isospin mixing in excited states will occur in light odd nuclei typically at excitation energies between $E_x = 6$ and 18 MeV, when neither the static criterion $D \gg \langle H_c \rangle$ nor the dynamic criterion $\hbar/\Gamma \ll \hbar/\langle H_c \rangle$ for isospin conservation[17,18] are fulfilled. Here, $\langle H_c \rangle$ is the average off-diagonal Coulomb matrix element responsible for the isospin mixing. The quantity $\langle H_c \rangle$ has been estimated[17] to be ≤ 100 keV and[19] ≈ 20 keV for light nuclei. The average level width Γ has been measured for many light nuclei and is found to increase with excitation energy E_x and to decrease with increasing A. Its dependence on E_x and A is well described[20] by the equation $\Gamma \approx \Gamma_0 \exp[\alpha(E_x/A)^{1/2}]$, where Γ_0 and α are empirical constants. Figure 4 shows estimated values for Γ as a function of excitation energy for ^{14}N, ^{18}F, and ^{30}P.

The considerations given above can explain the differing character of the contributions from compound-nucleus formation to the cross sections for isospin-nonconserving (d, α) reactions on carbon, oxygen, and silicon above about $E_d = 10$ MeV. At $E_x = 20$ MeV, for example (see Fig. 4 for the corresponding bombarding energies E_d), we have $\Gamma(^{14}\mathrm{N}) \approx 300$ keV, $\Gamma(^{18}\mathrm{F}) \approx 170$ keV, but $\Gamma(^{30}\mathrm{P}) \approx 45$ keV. Therefore, isospin-nonconserving compound-nucleus reactions in the lighter nuclei will require

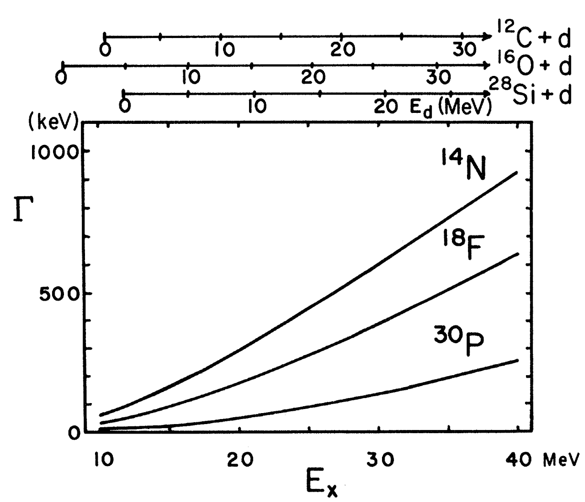

FIG. 4. Estimated average width Γ as a function of excitation energy E_x for the nuclei ^{14}N, ^{18}F, and ^{30}P. The deuteron bombarding energies E_d for the corresponding compound-nucleus reactions are shown on the top scale.

mostly pairs of states with very small values of Γ and/or large connecting matrix elements $\langle H_c \rangle$. Only selected states are likely to contribute. Relatively few isolated or overlapping resonances have indeed been observed, and it appears that the resonances seen around $E_d = 15$ MeV in the reactions on carbon and oxygen are the most energetic resonances of this type. It is intriguing, of course, to speculate on the nature of these states. The bands of cluster states suggested by Baz and Manko[14] could be considered, and even the special cluster states suggested by Weller.[9] The states postulated by Noble[3] provide another possible explanation. These are pairs of strongly isospin-mixed natural-parity states (except 0^+) based on the cluster configuration of a core plus a triplet *or* singlet deuteron in a state of relative angular momentum $L \neq 0$. For these states the charge-dependent perturbation is based on a combination of the nuclear spin-orbit and the Coulomb interaction and would indeed be stronger than that induced by H_c alone.

In ^{30}P, on the other hand, the dynamic criterion is still violated at $E_x \approx 20$ MeV. Since $\Gamma \gg D$, one expects Ericson fluctuations, which have indeed been observed[8,19] for bombarding energies E_d from 7 to 11 MeV and 12 to 17 MeV, respectively. The upper energy range corresponds to excitation energies E_x from about 23 to 28 MeV. Here, the estimated coherence width Γ increases from about 70 to 110 keV in perfect agreement with the observed value[8] of 100 keV. The reported decrease in cross section (≈ 2 μb/sr at $E_d \approx 16.5$ MeV) reflects the effect of the dynamic criterion, which is satisfied better at the higher energies.

It should be noted that the discussion given above could be refined by considering the spins J of the compound-nucleus states. The region of maximum isospin violation, for example, depends[18] on J. However, the general statements made above are only little affected.

Similar arguments can now be given in favor of a direct- or semidirect-reaction mechanism at least for the reaction ^{12}C$(d, \alpha)^{10}$B*(1.74 MeV) at bombarding energies E_d from about 26 to 30 MeV. These bombarding energies correspond to excitation energies E_x of about 32.5 to 35.5 MeV in the compound system ^{14}N. Here, the estimated width Γ is about 700 to 800 keV. The dynamic criterion should therefore practically exclude any contributions from isospin-nonconserving compound-nucleus reactions even if only states of a special nature contribute, as appears to be the case below $E_d \approx 15$ MeV.

A direct- or semidirect-reaction mechanism is also favored by the fact that the forward-angle differential cross section remains practically unchanged over a range of 14 MeV from about 16-MeV bombarding energy on. In a compound-nucleus reaction one would expect a sharp decrease in cross section due to the dynamic criterion, since the width of the states in the compound nucleus ^{14}N increases from about 400 keV by a factor of about 2. The shape of the measured angular distributions and the strength of the transitions are in agreement with estimates[2] for two semidirect isospin-nonconserving reaction mechanisms, namely, for virtual $E1$ Coulomb excitation of the deuteron (polarization of the deuteron in the Coulomb field of the target nucleus[5,2]) and for the preferential spin-flip mechanism in the deuteron suggested by Noble.[3,4]

The situation for the isospin-nonconserving reactions on oxygen and silicon is not as clear. The experimental evidence for the reaction on oxygen above $E_d = 16$ MeV, supported by arguments similar to those given above, also seems to favor a direct- or semidirect-reaction mechanism. However, additional evidence and particularly measurements at higher bombarding energies are desirable. The experimental results[8] for the reaction $^{28}Si(d, \alpha)^{26}Al^*(0.23$ MeV) are in full agreement with a compound-nucleus mechanism. It should be noted, however, that the energy correlation coefficient $C(0)$ measured by Richter *et al.*[8] does allow for interference with direct contributions which could be as strong as $\sigma_{direct}/\sigma_{comp.\,nucl.} \approx 0.5 \pm 1.0$ and would therefore accommodate a direct cross section of 5 μb/sr at 20°.

IV. CONCLUSIONS

The characteristics of the isospin-nonconserving reaction $^{12}C(d, \alpha)^{10}B^*(1.74$ MeV) measured at bombarding energies from about 26 to 30 MeV favor a direct- or semidirect-reaction mechanism. The experimental observations are supported by arguments related to the properties of the states in the compound system. Two semidirect-reaction mechanisms appear to be consistent with the observed facts, namely, virtual $E1$ Coulomb excitation of the deuteron[5,2] and a preferential spin-flip of one of the nucleons in the deuteron when it approaches the target nucleus.[3,4] No evidence has been obtained for contributions from the isospin-nonconserving two-step process suggested by Noble,[6] involving isospin-mixed 2^+ states in ^6Li or ^8Be.

Resonances observed in the reactions on oxygen and carbon[2,7] at bombarding energies near and below $E_d = 15$ MeV are probably due to compound-nucleus resonances involving selected states in the compound nucleus, but definite confirmation for some of these resonances is still forthcoming.

The A and E_x dependence of the width Γ of compound-nucleus states,[20] in conjunction with the dynamic criterion for isospin conservation,[17,18] seems to account (see Müller[16]) for the varying characteristics observed for isospin-nonconserving (d, α) reactions on light nuclei. These range from relatively few resonances apparently due to selected states in the compound nucleus on the one hand, to Ericson fluctuations on the other.

[1] L. Meyer-Schützmeister, D. von Ehrenstein, and R. G. Allas, Phys. Rev. 147, 743 (1966).

[2] J. Jänecke, T. F. Yang, R. M. Polichar, and W. S. Gray, Phys. Rev. 175, 1301 (1968).

[3] J. V. Noble, Phys. Rev. 162, 934 (1967).

[4] J. V. Noble, Phys. Rev. 173, 1034 (1968).

[5] Y. Hashimoto and W. P. Alford, Phys. Rev. 116, 981 (1959); R. J. Drachman, Phys. Rev. Letters 17, 1017 (1966); T. A. Griffy, Phys. Letters 21, 693 (1966); R. G. Clarkson and T. A. Griffy, Bull. Am. Phys. Soc. 12, 207 (1967).

[6] J. V. Noble, Phys. Rev. Letters 22, 473 (1969).

[7] H. V. Smith and H. T. Richards, Phys. Rev. Letters 23, 1409 (1969).

[8] A. Richter, L. Meyer-Schützmeister, J. C. Stoltzfus, and D. von Ehrenstein, Phys. Rev. C 2, 1361 (1970).

[9] H. R. Weller, Phys. Rev. C 2, 321 (1970).

[10] H. V. Smith and H. T. Richards, Phys. Rev. (to be published).

[11] Preliminary results on the reaction $^{16}O(d, \alpha)^{14}N^*$ (2.31 MeV) were reported by R. M. Polichar, J. Jänecke, T. F. Yang, and W. S. Gray, Bull. Am. Phys. Soc. 13, 1425 (1968).

[12] J. Jobst, S. Messelt, and H. T. Richards, Phys. Rev. 178, 1663 (1969).

[13] P. L. Jolivette and H. T. Richards, Phys. Rev. 188, 1660 (1969).

[14] A. I. Baz and V. I. Manko, Phys. Letters 28B, 541 (1969).

[15] P. B. Tollefsrud and P. L. Jolivette, Phys. Rev. C 1, 398 (1970).

[16] K. Müller, Nucl. Phys. 86, 56 (1966).

[17] D. H. Wilkinson, Phil. Mag. 1, 379 (1956).

[18] A. M. Lane and R. G. Thomas, Rev. Mod. Phys. 30, 257 (1958).

[19] P. G. Bizetti and A. M. Bizetti-Sona, Nucl. Phys. A108, 274 (1968).

[20] T. Ericson and T. Meyer-Kuckuk, Ann. Rev. Nucl. Sci. 16, 183 (1966).