Title
THE NC^^d)1 0 REACTION AT kO MeV

Permalink
https://escholarship.org/uc/item/2vc945pz

Authors
Zisman, M.S.
McClatchie, E.A.
Harvey, B.G.

Publication Date
1970-06-01

Submitted to Physical Review

UCRL-19914
Preprint

c. 2

THE $^{14}N(\alpha, d)^{16}O$ REACTION AT 40 MeV

M. S. Zisman, E. A. McClatchie, and B. G. Harvey

June 1970

AEC Contract No. W-7405-eng-48

LAWRENCE RADIATION LABORATORY
UNIVERSITY of CALIFORNIA BERKELEY

DISCLAIMER

THE $^{14}N(\alpha,d)^{16}O$ REACTION AT 40 MeV*

M. S. Zisman, E. A. McClatchie†, and B. G. Harvey

Lawrence Radiation Laboratory
University of California
Berkeley, California 94720

June 1970

ABSTRACT

The $^{14}N(\alpha,d)^{16}O$ reaction has been investigated up to an excitation energy of 20 MeV using a 40 MeV α-particle beam from the Berkeley 88-inch cyclotron. Angular distributions were obtained for the three strongest levels at 14.40 ± 0.03, 14.82 ± 0.03, and 16.24 ± 0.04 MeV. Widths for these states, with the experimental resolution subtracted in quadrature, are 30 ± 30, 69 ± 30, and 125 ± 50 keV, respectively. Evidence for the probable $[^{14}N(1^+) + (d_{5/2})^2_{5^+}]$ configuration of the three states is discussed.

INTRODUCTION

In recent years a study of the (α,d) reaction in various mass regions[1-5] has been undertaken in order to identify certain two-particle excited states in the final nucleus whose configuration can be described as

$$[J_t + (j)^2_{J=2j}]_{J_f} \quad ,$$

where J_t is the target spin, j is the spin of the shell-model state into which the transferred nucleons are captured, and J_f is the spin of the final state formed from vector coupling J_t and J. In most of the previous work[2,4] the targets were even-even, in which case $J_t = 0$ and only a single state of the above configuration was possible. However, in a few cases with $J_t \neq 0$ a multiplet of states was observed.[1,3,5] In particular, a triplet of states was observed in the doubly-magic ^{16}O nucleus via the $^{14}N(\alpha,d)^{16}O$ reaction at $E_\alpha = 42$ MeV.[3] These states were at excitation energies of 14.33 ± 0.10, 14.74 ± 0.10, and 16.16 ± 0.10 MeV, and were tentatively assigned the spin sequence 4^+, 6^+, 5^+ based on the $2J + 1$ rule.[3]

The highest member of the triplet, at 16.16 MeV, was found to be nearly degenerate with a 4p-4h state observed by Carter et al.[6] at 16.2 MeV in the $^{12}C(\alpha,\alpha_0)^{12}C$ resonance reaction and identified by them as the 6^+ member of the 4p-4h rotational band built upon the 6.05 MeV 0^+ state of ^{16}O. This left open the possibility that the two reactions were actually populating the same state. If this were true, of course, the mixing of a 2p-2h and 4p-4h configuration might invalidate the $2J + 1$ dependence of the cross section. Thus, the question of whether these states could be interpreted as belonging to the simple configuration $[^{14}N(1^+)+(d_{5/2})^2_{5^+}]_{4^+,5^+,6^+}$ was somewhat in doubt.

In order to help remove this ambiguity from the previous results it was decided to re-investigate the $^{14}N(\alpha,d)^{16}O$ reaction with better resolution than the 250 keV attained in the previous work.[3] In this way we could improve the accuracy of both the positions and the widths of the triplet and possibly obtain more information on the tentative spin assignments[3] based on the 2J + 1 rule.

EXPERIMENTAL

The experiment was performed using a 40 MeV α-particle beam from the Berkeley 88-inch cyclotron. Two 110-deg uniform-field magnets[7] were used to provide energy analysis of the beam. Object and image slit widths of 1 mm produced a beam resolution, $\Delta E/E$, of 0.04%. In order to take advantage of the improved beam resolution, a gas cell with a thin entrance window was employed. The cell consisted of a stainless steel cylinder 7.6 cm in diameter and 2.5 cm high with an exit foil of 2.1 mg/cm^2 Havar covering 315 deg. The remaining solid section of the cell was bored out and fitted with a hollow brass plug on the end of which a 0.22 mg/cm^2 Ni entrance foil was epoxied. A circular tantalum collimator 3.8 mm in diameter was used to define the beam entering the gas target. Several anti-scattering slits were employed to further define the beam and to protect the edge of the thin entrance window. The Ta collimator was electrically insulated from the gas cell in order to monitor the untransmitted beam. By careful attention to the beam optics it was possible to hold the beam loss to less than 1% during the course of the run.

The target consisted of natural nitrogen (99.6% ^{14}N) at a pressure of about 30 Torr. Deuterons from the target were detected in 0.25 mm ΔE and 3 mm E detectors and identified with a Goulding-Landis particle identifier.[8] The rest of the system has been described previously.[3]

RESULTS

A deuteron spectrum of the $^{14}N(\alpha,d)^{16}O$ reaction at $\theta_{\ell} = 10$ deg is shown in Fig. 1. The resolution was 66 keV (FWHM) for the narrow states of ^{16}O. Since a biased amplifier was used to look selectively at the high-excitation region of ^{16}O, the ground state does not appear at any angle and the first two excited states, at 6.05 and 6.13 MeV, are visible only at the more backward angles. The peak position is consistent with our observing only the 6.13 MeV, 3^-, member of the 6 MeV doublet. It can be seen that even with this improved experimental resolution the three members of the previously observed[3] triplet still appear as single states. However, a new state at 15.8 MeV, which was unresolved in the earlier work,[3] is now visible. The excitation energies determined from this work for the three largest states are 14.40 ± 0.03, 14.82 ± 0.03, and 16.24 ± 0.04 MeV.

Angular distributions for the triplet from $\theta_{cm} = 12.9$ to 57.7 deg are shown in Fig. 2. As was observed in the earlier work,[2,3,5] the angular distributions tend to be rather structureless and decrease almost exponentially with angle. This feature is related to the large angular momentum transfer in the reaction and has been discussed previously.[3] The integrated cross sections for these states (from $\theta_{cm} = 12.9$ to 57.7 deg), after background subtraction, are 1.52, 2.90, and 1.91 mb. In Ref. 3 the cross section of the 15.8 MeV state was contributing to that of the 16.16 MeV level. This amounts to a correction of about 13% to the cross section reported[3] for the 16.16 MeV state. The reduced cross sections, after dividing by $[(2J_f + 1)/(2J_t + 1)]$, are 0.51, 0.67, and 0.52 mb, respectively. The uncertainty in the absolute cross sections is estimated to be about 10%.

Widths were obtained for all three states based on an average of seven runs at five angles. The values for Γ_{cm} (with the experimental resolution subtracted in quadrature) as well as previously measured widths for nearby $T = 0$ levels are given in Table I. The difficulty in obtaining accurate widths for the states was due to uncertainties in the background subtraction and to the experimental resolution. The latter was particularly important for the 14.40 MeV state, whose width is small compared to the resolution. In fact, in two of the seven runs the observed width (after background subtraction) was consistent with those of the lower energy, sharp states in ^{16}O. The problem of background subtraction was most severe for the 16.24 MeV state since it has a large width and, at backward angles, the peak shape was poorly defined.

Other strong states populated in the reaction include the 8.87, 11.09, and 17.17 MeV levels. The 6.13 MeV state was populated rather strongly at all angles where it was included, and had a differential cross section comparable to that of the 11.09 MeV state. The "state" near 14.0 MeV contains a contribution of unknown amount from the 1.131 MeV level of ^{18}F due to the (α,d) reaction on a small oxygen contaminant in the target. The cross section leading to this ^{18}F state (whose configuration is $[^{16}O + (d_{5/2})^2_{5+}])^3$ is very large and the state is visible in nearly all (α,d) experiments. Due to this impurity it was not possible to get a precise value for the excitation energy of the 14 MeV state, since the kinematics of the two states differ only slightly and thus the apparent energy of the peak changes somewhat with angle. A summary of the states observed in this experiment and their intensities is given in Table II.

DISCUSSION

A. $[^{14}N(1^+) + (d_{5/2})^2_{5^+}]$ Levels

Figure 1 indicates the selectivity of the (α,d) reaction in populating the various final states in ^{16}O. Aside from the triplet of states at 14.40, 14.82, and 16.24 MeV, the only other strongly-populated states are those at 8.87 and 11.09 MeV. (At backward angles where the 6.13 MeV level could be observed it was also found to be populated strongly.) In part this selectivity is based on the kinematics of the reaction, i.e., on the fact that the semi-classical angular momentum transfer, $\vec{Q} \times \vec{R}$, is large.[3,5] However, due to the 1^+ spin of the target nucleus, the number of possible L values for a given transition is increased, with the result that selection rules allow $L \geqslant 2$ for all values of J_f^π except 0^-. Since the maximum angular momentum transfer expected for placing two nucleons in the sd shell is $L = 4$, this form of selectivity is somewhat reduced.

The other reason for selectively populating certain final states is that two-nucleon transfer reactions are, in general, quite sensitive to the details of nuclear structure. This form of selectivity has been discussed in detail by Glendenning.[9] In his notation, the states which may be strongly populated are those with a large "structure factor", i.e., those states whose wave functions are predominantly of the form [target core + deuteron] for the (α,d) reaction. This implies that the final states in ^{16}O which are preferentially populated should be those described as 1p-1h or 2p-2h with respect to the ^{16}O core, since the target wave function[10] is about 93% $(p_{1/2})^{-2}_{1^+}$. It has been suggested for some time that certain states in ^{16}O exhibit a rotational-band structure[6,11] based on the 0^+ state at 6.05 MeV. This result has been reproduced with various calculations[12-15] involving a mixture of 4p-4h and 2p-2h configurations in a deformed basis. The nature of the lowest even-parity band is believed to be mainly 4p-4h.[14,15] Clearly such states should not be strongly populated in a two-particle transfer reaction on a target which has only about 7% admixture of 2p-4h configurations in the ground state.[10]

Our data is consistent with the dominant 4p-4h interpretation of the states in ^{16}O assigned to the rotational band. As can be seen in Fig. 1, the 6.92 and 10.35 MeV states, a 2^+ and 4^+, respectively, are both populated rather weakly. The angular distribution for the 10.35 MeV level is quite different from those of the strong states, being relatively flat as opposed to the rather steep envelope typical of the strongly-populated levels. This result has been observed previously[2,5] in (α,d) reactions leading to weakly-populated final states. The angular distribution of the 6.92 MeV level has not been extracted since it was obscured by the pulser at most angles. At those angles where the 6.13 MeV level appeared, it had a width consistent with only a single state being populated. However, assuming the 6.05 MeV state has a cross section similar to those of the other 4p-4h states (or to that of the other excited 0^+ state[16] at 12.05 MeV) we would not expect it to be visible next to the much stronger 3^- level. On this basis we feel that strong population of the 4p-4h 6^+ state observed in the α- ^{12}C resonance work[6] is highly unlikely.

The α- ^{12}C resonance experiment[6,17] yields a width for the 16.2 MeV 6^+ state of $\Gamma_{cm} = 320 \pm 90$ keV. This is to be compared with a value from this work of $\Gamma_{cm} = 125 \pm 50$ keV for the 16.24 MeV level. In contrast to the rather large width quoted[6,17] for the 16.2 MeV, 4p-4h, 6^+ level, we note that there are other natural-parity levels in ^{16}O which, although unbound by a large amount, have very small α-widths. For example, the 12.05 MeV 0^+ level is unbound by nearly 5 MeV and yet it shows up as a very weak α-resonance with a measured width of only 1.5 ± 0.5 keV,[16] while the 10.35 MeV 4^+ state, which is a member of the 4p-4h band, has a width of 27 ± 8 keV[18] for a lower energy L = 4 α-decay. The 0^+ level, however, is believed to be the predominantly 2p-2h member of the triplet of 0^+ states arising from a mixture of 0p-0h, 2p-2h, and 4p-4h states,[15] and thus has a configuration which overlaps poorly with $[^{12}C + \alpha]$. This interpretation is consistent with our data inasmuch as the integrated cross section for the 12.05 MeV state is about half that for the 10.35 MeV level. This yields a reduced cross section about four times larger for the 0^+ state, in spite of the fact that the 0^+ population would be expected to be somewhat hindered on the basis of the kinematics argument mentioned above. It would seem, therefore, that the large width and the strong α-resonance characteristic of the 16.2 MeV level observed by Carter _et al._[6] suggest a dominant 4p-4h configuration for that state.

Another way of comparing the large states observed in the $^{14}N(\alpha,d)^{16}O$ reaction with levels of 4p-4h configuration is to look at the results of the 4-nucleon transfer reactions leading to ^{16}O. These should preferentially populate 4p-4h states if the reaction mechanism corresponds to a direct α-particle transfer. The $^{12}C(^{6}Li,d)^{16}O$ reaction[19-21] and $^{12}C(^{7}Li,t)^{16}O$ reaction[20-22] have both been observed by various groups. The $^{12}C(^{6}Li,d)^{16}O$ reaction[19] shows strong population of the 10.35 MeV 4^+ level and also shows large cross sections to states at about 14.4, 14.8, and 16.22 MeV. The $^{12}C(^{7}Li,t)^{16}O$ results[20,22] are essentially identical, showing strong population of the 10.35 MeV state and broad structure at 14-15 MeV and 16.2 MeV. The interpretation of these results, of course, requires some knowledge of the reaction mechanism. In the case of direct α-particle transfer the final states expected would be only natural-parity, $T = 0$ levels, although in either reaction the selection rules allow formation of unnatural-parity states and in the $(^{7}\mathrm{Li},t)$ reaction $T = 1$ levels are also allowed. Bethge *et al.*[21] have made a careful comparison of both reactions and conclude that, while the $(^{6}\mathrm{Li},d)$ reaction seems to have some compound-nucleus contributions, the $^{12}\mathrm{C}(^{7}\mathrm{Li},t)^{16}\mathrm{O}$ reaction, at least at 20 MeV, can be interpreted as an α-particle transfer reaction. It appears that the strongest states observed in both reactions can be understood in terms of α-particle transfer. This allows population of np-nh states of $^{16}\mathrm{O}$, where $0 \leqslant n \leqslant 4$, assuming that the $^{12}\mathrm{C}$ ground state is mainly 0p-4h. A comparison of our $^{14}\mathrm{N}(\alpha,d)^{16}\mathrm{O}$ data with the above results indicates that both the four- and two-particle transfer reactions show strength for states at about 14.5 and 16.2 MeV. The 16.2 MeV level appears very broad in the 4-particle transfer data,[19,20] but no widths are quoted for it.

Recently there has been some new evidence about the states in this energy region from the $^{13}\mathrm{C}(^{6}\mathrm{Li},t)^{16}\mathrm{O}$ reaction[23] at $E_{^{6}\mathrm{Li}} = 20$ MeV. The interpretation of this reaction is somewhat uncertain but Bassani *et al.* feel that, based on the structure and forward-peaking of their angular distributions, there is a significant direct-reaction contribution to their data. If this is correct then 1p-1h, 2p-2h, and 3p-3h states should be easily populated. There is a strong resemblance between our (α,d) data and the $(^{6}\mathrm{Li},t)$ data of Bassani *et al.*[23] Both show states at 14.4 and 14.8 MeV as well as a state at 16.2 MeV, and both show strong population of the 11.09 MeV doublet, with weaker population of the 10.35 MeV, 4^{+}, level. Other levels observed in both reactions include the 12.05 and 12.53 MeV states. The $^{13}\mathrm{C}(^{6}\mathrm{Li},t)^{16}\mathrm{O}$ data also gives evidence for the existence of two different states at 16.2 MeV. At backward angles, where the $^{12}C(^6Li,t)^{15}O$ impurity peak has moved away from the 16.2 MeV excitation region, the peak observed in the 3-nucleon transfer reaction at 16.2 MeV is much sharper than that observed in the $^{12}C(^6Li,d)^{16}O$ reaction.[24] This tends to confirm our belief that there are two distinct states in this region, one of which is the broad state of 4p-4h nature[6,19-22] and the other of which is a 2p-2h state whose dominant configuration is $[^{14}N(1^+) + (d_{5/2})^2_{5^+}]$. The fact that the 4-particle transfer reactions appear to populate the states at 14.4 and 14.8 MeV that are observed in the (α,d) reaction may indicate that 4-particle transfer reactions can populate both states in the 16.2 MeV region, while the $^{13}C(^6Li,t)^{16}O$ and $^{14}N(\alpha,d)^{16}O$ reactions are able to strongly populate only the 2p-2h level. It should be noted, however, that one of the triplet of states of configuration $[^{14}N(1^+) + (d_{5/2})^2_{5^+}]$ has unnatural parity and therefore should not be strongly populated with an α-transfer reaction.

Additional support for our interpretation of the 14.40, 14.82, and 16.24 MeV levels of ^{16}O as a $[^{14}N(1^+) + (d_{5/2})^2_{5^+}]_{4^+,5^+,6^+}$ triplet comes from the shell model calculations of Zuker, Buck, and McGrory[25] (referred to hereafter as ZBM). ZBM perform a complete diagonalization in the space of up to 4 particles in the $1p_{1/2}$, $1d_{5/2}$, and $2s_{1/2}$ orbitals and predict the existence of very pure ($\gtrsim 95\%$) 6^+ and 5^+ states of the above configuration which essentially do not mix with the 4p-4h levels.[25] The purity of these states is very insensitive to changes in either the matrix elements or the single-particle energies used in the calculation. Based on the matrix element set B in Ref. 25, the states are predicted at 13.4 and 14.4 MeV, with the 6^+ being lower. This ordering is also more or less independent of the choice of matrix elements and single-particle energies, although adjustments in these quantities do alter the predicted excitation energies and splitting somewhat. The existence of a nearby 4p-4h 6^+ state, containing less than 1% admixture of 2p-2h configuration, is also predicted in this model. The fact that the 4p-4h state is calculated to be at 16.9 MeV (again using matrix element set B) is consistent with the interpretation by Carter et al.[6] of the 16.2 MeV 6^+ resonance as a 4p-4h state.

The situation for the 4^+ state is, unfortunately, not so clearcut. The ZBM results predict appreciable mixing of this state, both with 4p-4h components and with other 2p-2h configurations. There are two 4^+ states (referred to as 4_3^+ and 4_4^+ in ZBM) expected to carry the major part of the $(d_{5/2})^2_{5^+}$ strength. The results from matrix element set B indicate that the (α,d) strength would go mainly to the upper, 4_4^+, state at an excitation energy of 15.8 MeV. However, this prediction is sensitive to the choice of matrix elements, since the wave functions for 4_3^+ and 4_4^+ essentially interchange in going to matrix element set A1, with the result that the lower 4^+ level now becomes the (expected) stronger (α,d) transition. The results for the 4^+ level would also be less certain than those for the 5^+ and 6^+ levels if there are any effects due to the omission of the $d_{3/2}$ orbital, since even a relatively small amount of $(d_{3/2})^2_{3^+}$ configuration would alter the expected strengths of the various 4^+ levels significantly.

The spin sequence predicted[25] from this model for the $[^{14}N(1^+) + (d_{5/2})^2_{5^+}]$ triplet is 6^+, 5^+, 4^+, in order of increasing excitation energy. Our reduced cross sections give identical values for the 14.40 and 16.24 MeV states, with the 14.82 MeV state having comparatively more (α,d) strength. This is based on a spin sequence 4^+, 6^+, 5^+ since the observed cross sections are $\sigma_{14.82} > \sigma_{16.24} > \sigma_{14.40}$. The application of the 2J + 1 rule to two-nucleon transfer reactions seems rather dangerous, however, due to the coherent dependence of the cross section on the wave function.[9] In this case, the cross sections of the nearly pure 6^+ and 5^+ states will be affected by the overlap of the small 2p-4h components[10] in ^{14}N with the 4p-4h components[25] in ^{16}O, while the cross section of the 4^+ state depends not only on these admixtures but also on the other 2p-2h components, e.g., $(d_{5/2})^2_{3^+}$ and $(d_{5/2}s_{1/2})_{3^+}$, which can be populated directly through the dominant part of the ^{14}N ground state. Thus, while the results of the ZBM calculation[25] do indicate the existence of a relatively pure triplet of states of configuration $[^{14}N(1^+) + (d_{5/2})^2_{5^+}]_{4^+,5^+,6^+}$ in the energy region of our observed states, any ordering of the states based on the relative cross sections[3] is highly uncertain.

B. Other Levels

The only other strong positive-parity peak observed in this reaction is the 11.09 MeV doublet. These states, at 11.080 and 11.094 MeV, were both observed in the $^{14}N(^3He,p)^{16}O$ reaction[18] and the lower member was assigned $J^\pi = 3^+$ in the $^{14}N(^3He,p\ \gamma\gamma)^{16}O$ reaction.[26] The upper member was observed in the $^{12}C(\alpha,\alpha_0)^{12}C$ reaction[16] and assigned $J^\pi = 4^+$ with a width $\Gamma_{cm} = 0.3 \pm 0.1$ keV. This doublet was also seen in the $^{12}C(^6Li,d)$ and $^{12}C(^7Li,t)$ reactions[19,21] and, as mentioned above, was the most intense triton group observed in the $^{13}C(^6Li,t)^{16}O$ reaction.[23] Our results, as well as those of the $^{12}C(^7Li,t)$[21] and $^{13}C(^6Li,t)$[23] reactions, seem to indicate that it is mainly the upper member of the doublet which is being populated, based on the observed energy of the peak. In the $(^7Li,t)$ reaction the cross sections for exciting other unnatural-parity states are essentially zero[21] so that a large contribution of the 11.08 MeV level to the observed peak would seem unlikely. The two- and three-nucleon transfer reactions are not forbidden to populate unnatural parity states and hence a contribution from the 3^+ member of the doublet cannot be ruled out. The fact that both states of the doublet were observed in the $^{14}N(^3He,p)^{16}O$ reaction[18] is not necessarily a good indication of what will be observed in the $^{14}N(\alpha,d)^{16}O$ reaction, since the former work was done at such a low energy ($E_{^3He}$ = 3.74 MeV).

The ZBM calculations[25] predict a pair of levels with $J^\pi = 3^+, 4^+$ which appear rather close together (E_{3^+} = 13.39 MeV, E_{4^+} = 13.02 MeV) although the order is inverted and the energies are too high. These states both contain large amplitudes of the 2p-2h configurations $(d_{5/2}\ s_{1/2})_{3^+}$ and $(d_{5/2})^2_{3^+}$ which have fairly large L = 2 structure factors[9] for formation in the $^{14}N(\alpha,d)^{16}O$ reaction. If the association of these levels with the observed doublet at 11.09 MeV is correct, the peak should contain comparable contributions from both levels, but our resolution is not adequate to determine whether or not this is true. The weak population of the 4^+ level in the $(^7Li,t)$ reaction[21] and the small α-width[16] are both consistent with a dominant 2p-2h configuration for this level.

The negative-parity levels in ^{16}O which are strongly populated in the $^{14}N(\alpha,d)^{16}O$ reaction should be those with a 1p-1h configuration. The 6.13 and 8.87 MeV levels, 3^- and 2^- respectively, are both described as having large amplitudes of the $(p^{-1}_{1/2}\ d_{5/2})$ configuration,[25,27] which overlaps well[9] with the [target core + deuteron] structure expected for the strongly-populated levels in the (α,d) reaction. Both levels were excited with an $\ell = 2$ transition in the $^{15}N(^3He,d)^{16}O$ reaction,[28] in agreement with this picture. The other negative-parity state excited in our work, at 12.53 MeV, has also been observed in the $^{15}N(^{3}He,d)^{16}O$ experiment[28] and is described as being mainly a $(p^{-1}_{1/2}\ d_{3/2})_{2-}$ level. Fulbright et al.[28] have shown that nearly all of the $d_{3/2}$ proton strength can be accounted for in this one state; this is consistent with the weak population of the level in the $^{17}O(p,d)^{16}O$ experiment.[29] This state would also be expected to be populated in the (α,d) reaction based on Glendenning's structure factors.[9]

The spin and parity of the 15.80 MeV level have not been established. It was observed recently by Comfort et al.[30] in the $^{14}N(^{3}He,p)^{16}O$ reaction and their data suggested a T = 0 assignment, since no analog in ^{16}N is known. A preliminary analysis of the $(^{3}He,p)$ data[30] yielded a width of about 40 keV for the 15.80 MeV level, but no L-value was assigned. The appearance of this state in our $^{14}N(\alpha,d)^{16}O$ data confirms that it is a T = 0 level. We obtain a width for the 15.80 MeV level of approximately 60 keV, but the low cross section and the position of the peak preclude anything but a rough estimate of this quantity.

The highest sharp state observed in this work is at 17.17 ± 0.04 MeV. States in this region have also been observed in the α- ^{12}C and p- ^{15}N resonance reactions[6,31] at 17.10 and 17.14 ± 0.015 MeV, respectively, in the $^{14}N(^{3}He,p)^{16}O$ reaction[30] at 17.14 ± 0.02 MeV, and in the $^{15}N(^{3}He,d)^{16}O$ reaction[28] at 17.12 MeV. The state observed in the p- ^{15}N resonance was assigned J = 1 and has $\Gamma_{cm} = 33 \pm 5$ keV.[31] It is assumed to be the T = 1 analog of the 4.32 MeV, 1^{+}, level in ^{16}N, based on the fact that its observed width is much less than that of the T = 0 resonance observed by Carter et al.[6] at 17.10 MeV with $\Gamma_{cm} = 110$ keV and $J^{\pi} = (1^{-}, 0^{+}, 2^{+})$. The $^{14}N(^{3}He,p)^{16}O$ data[30] yield a value of $\Gamma_{cm} \approx 80$ keV for the 17.14 MeV level. It would appear that this level has a much larger width than that of the known[31] T = 1 resonance. Our data indicate a width of approximately 70 keV for the 17.17 MeV state, but this is rather uncertain due to background subtraction. If the 17.17 MeV level observed here is identical to that observed by Comfort et al.[30] at 17.14 MeV then a T = 0 assignment is required, and the $^{14}N(^{3}He,p)^{16}O$ reaction would proceed by an S = 1 transfer. This would allow a final state of $J^{\pi} = 0^{+}, 1^{+}$, or 2^{+} (assuming the L = 0 assignment is correct). The 17.12 MeV level observed by Fulbright et al.[28] in the $^{15}N(^{3}He,d)^{16}O$ reaction is believed to be a negative-parity state, since its strength would be inconsistent with a positive-parity assignment. However, no ℓ-value was determined in that work.

CONCLUSIONS

We have demonstrated that the selectivity observed in the (α,d) reaction can be understood, at least qualitatively, in terms of Glendenning's two-nucleon transfer formalism.[9] The states of known configuration which are populated can all be described as having mainly 1p-1h or 2p-2h components. The final states which are believed to be rotational (4p-4h) in nature are excited very weakly. The 16.24 MeV level observed in the $^{14}N(\alpha,d)^{16}O$ reaction has a much smaller width that the 4p-4h state observed by Carter *et al.*[6] and is believed to be a 2p-2h state whose major configuration is $[^{14}N(1^+) + (d_{5/2})^2_{5^+}]$. The 4p-4h 6^+ level would not be expected to be strongly excited based on the observed cross sections for the low-lying 4p-4h states. A narrow state at this energy has also been observed recently in the $^{13}C(^6Li,t)^{16}O$ data of Bassani *et al.*[23,24] Recent shell model calculations by Zuker, Buck, and McGrory[25] also lend support for the existence of a multiplet of very pure states which contain nearly all of the $(d_{5/2})^2_{5^+}$ strength. The 4^+ member of this multiplet is predicted to contain fairly large admixtures of other 2p-2h and 4p-4h components which may greatly affect the observed 2-nucleon transfer strength. Application of the 2J + 1 rule is, therefore, believed to be inappropriate for these levels.

Two excited states at 15.80 ± 0.04 and 17.17 ± 0.04 MeV, can be identified as T = 0 levels by this work. The 17.17 MeV level may be the same as that observed by Comfort *et al.*[30] in the $^{14}N(^3He,p)^{16}O$ reaction and tentatively identified by them as T = 1.

ACKNOWLEDGMENTS

We would like to thank Dr. A. D. Bacher for allowing us to use his modified gas target and for a careful reading of this paper. We are also indebted to Dr. T. A. Tombrello for loaning us the thin nickel foil used in this experiment, and to C. Maples for allowing us to use his computer code LORNA for some of the data analysis.

FOOTNOTES AND REFERENCES

[*] Work performed under the auspices of the U. S. Atomic Energy Commission.

[†] Present address: ARKON Scientific Labs., Berkeley, California.

1. J. Cerny, B. G. Harvey, and R. H. Pehl, Nucl. Phys. 29, 120 (1962).
2. R. H. Pehl, E. Rivet, J. Cerny, and B. G. Harvey, Phys. Rev. 137, B114 (1965).
3. E. Rivet, R. H. Pehl, J. Cerny, and B. G. Harvey, Phys. Rev. 141, 1021 (1966).
4. C. C. Lu, M. S. Zisman, and B. G. Harvey, Phys. Letters 27B, 217 (1968).
5. C. C. Lu, M. S. Zisman, and B. G. Harvey, Phys. Rev. 186, 1086 (1969).
6. E. B. Carter, G. E. Mitchell, and R. H. Davis, Phys. Rev. 133, B1421 (1964); G. E. Mitchell, E. B. Carter, and R. H. Davis, Phys. Rev. 133, B1434 (1964).
7. R. E. Hintz, F. B. Selph, W. S. Flood, B. G. Harvey, F. G. Resmini, and E. A. McClatchie, Nucl. Instr. Methods 72, 61 (1969).
8. F. S. Goulding, D. A. Landis, J. Cerny, and R. H. Pehl, Nucl. Instr. Methods 31, 1 (1964).
9. N. K. Glendenning, Phys. Rev. 137, B102 (1965); N. K. Glendenning, "Tables of Structure Amplitudes for (α,d) Reactions", Lawrence Radiation Laboratory Report UCRL-18270, (unpublished).
10. W. W. True, Phys. Rev. 130, 1530 (1963).
11. J. D. Larson and R. H. Spear, Nucl. Phys. 56, 497 (1964).
12. W. H. Bassichis and G. Ripka, Phys. Letters 15, 320 (1965).
13. I. Kelson, Phys. Letters 16, 143 (1965).
14. G. E. Brown and A. M. Green, Nucl. Phys. 75, 401 (1966).
15. L. S. Celenza, R. M. Dreizler, A. Klein, and G. J. Driess, Phys. Letters 23, 241 (1966).
16. J. D. Larson and T. A. Tombrello, Phys. Rev. 147, 760 (1966).
17. E. B. Carter, private communication.

18. C. P. Browne and I. Michael, Phys. Rev. 134, B133 (1964).

19. K. Meier-Ewert, K. Bethge, and K. -O. Pfeiffer, Nucl. Phys. A110, 142 (1968).

20. J. R. Comfort, H. T. Fortune, G. C. Morrison, and B. Zeidman, Contribution for International Conf. on Nuclear Reactions Induced by Heavy Ions, Heidelberg, Germany, July, 1969, (unpublished).

21. K. Bethge, K. Meier-Ewert, K. Pfeiffer, and R. Bock, Phys. Letters 24B, 663 (1967).

22. V. I. Chuev, V. V. Davidov, A. A. Ogloblin, and S. B. Sakuta, Arkiv för Fysik 36, 263 (1967).

23. G. Bassani, T. H. Kruse, N. Saunier, and G. Souchere, Phys. Letters 30B, 621 (1969).

24. G. Bassani, private communication.

25. A. P. Zuker, B. Buck, and J. B. McGrory, Phys. Rev. Letters 21, 39 (1968); A. P. Zuker, B. Buck, and J. B. McGrory, Brookhaven National Laboratory Report BNL-14085, (unpublished).

26. D. A. Bromley, H. E. Gove, J. A. Kuehner, A. E. Litherland, and E. Almqvist, Phys. Rev. 114, 758 (1959); J. A. Kuehner, A. E. Litherland, E. Almqvist, D. A. Bromley, and H. E. Gove, Phys. Rev. 114, 775 (1959).

27. J. P. Elliott and B. H. Flowers, Proc. Roy. Soc. 242, 57 (1957).

28. H. W. Fulbright, J. A. Robbins, M. Blann, D. G. Fleming, and H. S. Plendl, Phys. Rev. 184, 1068 (1969).

29. R. Mendelson, J. C. Hardy, and J. Cerny, Phys. Letters 31B, 126 (1970).

30. J. R. Comfort, J. E. E. Baglin, and M. N. Thompson, Bull. Am. Phys. Soc. 13, 608 (1968); J. R. Comfort, J. E. E. Baglin, and M. N. Thompson, Preliminary Report based on a talk presented at the Washington American Physical Society Meeting, April, 1968, (unpublished).

31. A. R. Barnett, Nucl. Phys. A120, 342 (1968).

Table I. Widths of Levels Observed in $^{14}N(\alpha,d)^{16}O$ as Compared to Previously Measured Nearby T=0 Level Widths.

This Work		Previously Measured[a]	
E_x (MeV)	Γ_{cm}[b] (keV)	E_x (MeV)	Γ_{cm} (keV)
14.40 ± 0.03	30 ± 30		
		14.72	400
14.82 ± 0.03	69 ± 30	14.8	40-60
		14.85	75
		15.42	60
		15.7	525
15.80 ± 0.04	(60)	15.8	300-400, ≈ 40[c]
16.24 ± 0.04	125 ± 50	16.2	320[d]
		16.41	60
		17.10	110
17.17 ± 0.04	(70)	17.14	≈ 80[c,e]

[a] Taken from Ref. 6 unless otherwise noted.

[b] With experimental resolution (≈ 75 keV) subtracted in quadrature.

[c] Ref. 31.

[d] This value was changed from that in Ref. 6 by Ref. 17.

[e] This state is possibly a T=1 analog to the ^{16}N(4.32 MeV) level.

Table II. Comparison of ^{16}O (T=0) Levels Observed in $^{14}N(\alpha,d)^{16}O$ With Those Reported Previously.

Levels Observed[a] (MeV ± keV)	T=0 Levels Previously Reported[b] (MeV)	J^{π} [b]	Intensity[c] (mb)
---[d]	0.0	0^+	
	6.052	0^+	
6.13	6.131	3^-	0.78[e]
6.92	6.916	2^+	weak
7.12	7.115	1^-	weak
8.87	8.870	2^-	0.62
	9.614	1^-	
9.85	9.847	2^+	0.10
10.35	10.353	4^+	0.16
	10.952	0^-	
	11.080	3^+	
11.09	11.096	4^+	1.01
	11.260	0^+	
11.52	11.521	2^+	0.24
	11.630	3^-	
12.05 ± 30	12.053	0^+[f]	0.08[g]
	12.437	1^-	
12.53	12.528	2^-	0.27
	Mainly T=1		

(continued)

Table II. Continued

Levels Observed[a] (MeV ± keV)	T=0 Levels Previously Reported[b] (MeV)	J^{π}[b]	Intensity[c] (mb)
	13.869	4^+	
(14.0)[h]	13.975	2^-	
14.40 ± 30			1.52
	14.6[i]	even[i]	
	14.72		
	14.78[i]	$(0^+,1^-)$[i]	
14.82 ± 30	14.81	0^+	2.90
	14.85[i]		
	14.922	4^+	
	15.22	2^-	
	15.26	2^+	
	15.42	3^-	
	15.7[i]	3^-[i]	
15.80 ± 40	15.80		0.25[j]
16.24 ± 40	16.2[i]	6^+	1.91
	16.3	1^+	
	16.45	0^-	
	17.10[i]	$(1^-,2^+,0^+)$[i]	
17.17 ± 40	17.13	1^-	0.45
	17.30	1^-	

(continued)

Table II. Continued

---

[a] All energies ± 15 keV unless otherwise specified.

[b] Information is taken from T. Lauritsen and F. Ajzenberg-Selove, Energy Levels of Light Nuclei, Nucl. Data Sheets, May, 1962 and Ref. 18, unless otherwise noted.

[c] Integrated cross section from θ_{cm} = 12.9 to 57.7 deg except as noted.

[d] The ground state was not observed due to the experimental conditions.

[e] Integrated from θ_{cm} = 30.5 to 54.3 deg.

[f] Ref. 16.

[g] Integrated from θ_{cm} = 12.7 to 49.9 deg.

[h] Contains contaminant peak due to the $^{16}O(\alpha,d)^{18}F$ reaction.

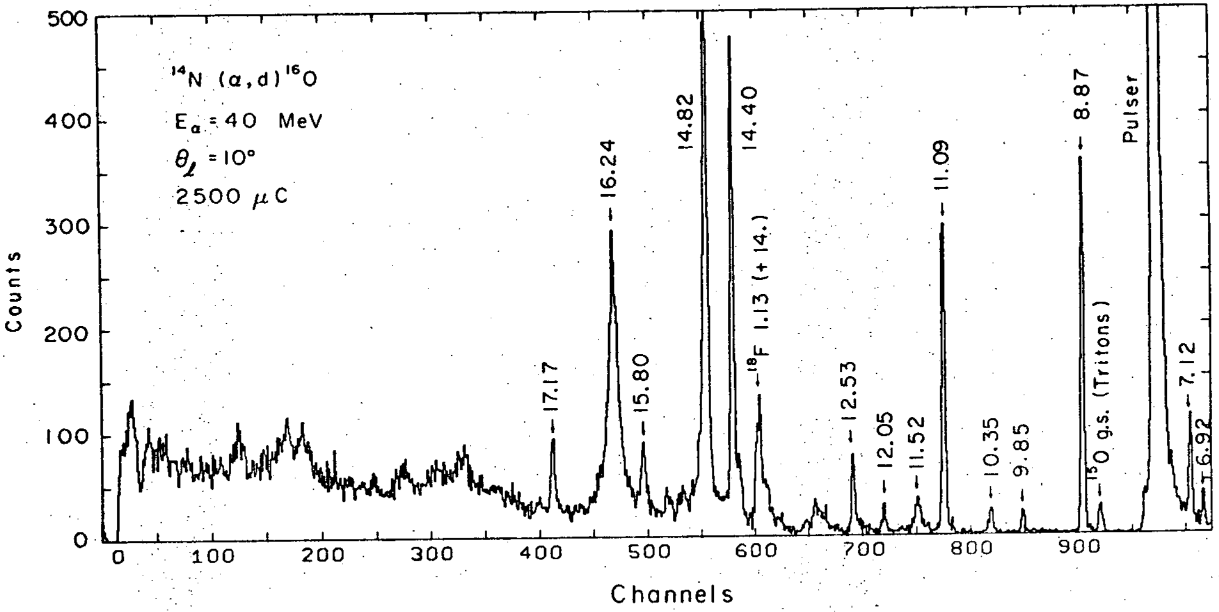
[i] Ref. 6.

[j] Integrated from θ_{cm} = 13.0 to 45.1 deg.

FIGURE CAPTIONS

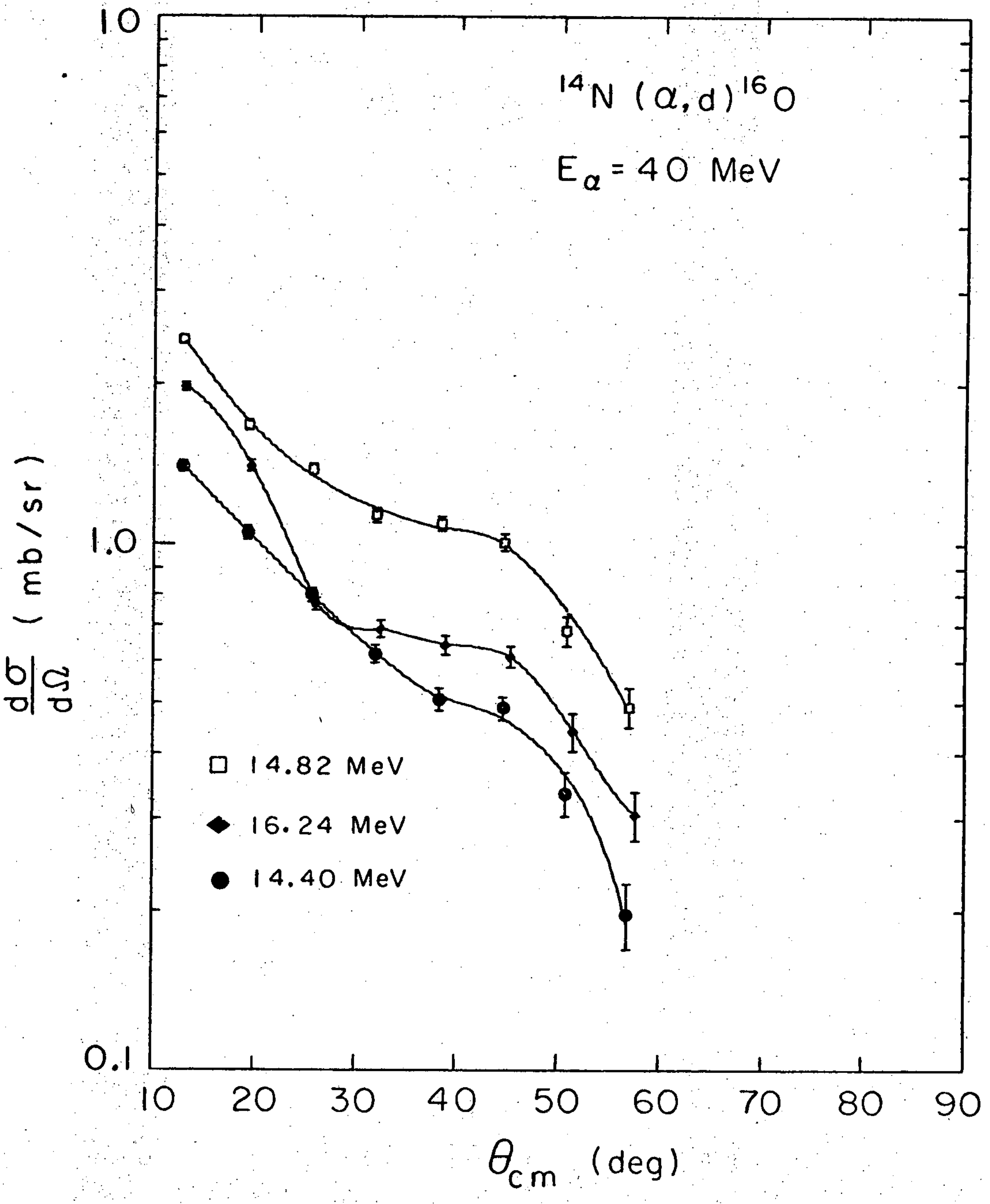
Fig. 1. Deuteron energy spectrum from the $^{14}N(\alpha,d)^{16}O$ reaction at $\theta_{\ell} = 10$ deg.

Fig. 2. Angular distributions of deuterons from the $^{14}N(\alpha,d)^{16}O$ reaction leading to the 14.40, 14.82, and 16.24 MeV levels. Statistical errors are indicated for each point. The curves have no theoretical significance.



XBL706-3087

Fig. 1



XBL706-3086

Fig. 2

TECHNICAL INFORMATION DIVISION
LAWRENCE RADIATION LABORATORY
UNIVERSITY OF CALIFORNIA
BERKELEY, CALIFORNIA 94720