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Alpha-cluster levels in ^{15}O as seen in the reaction ^{14}N(p, α_0)^{11}C†

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Excitation functions and angular distributions of ^{14}N(p, α_0)^{11}C for bombarding energies of 9.0 through 12.0 MeV have been measured in steps of 50 keV from 10 through 160°. Prominent structures are noted near excitations of 16.2, 17.2, and 17.8 MeV in ^{15}O and are observed to be composed of many sub-structures. Legendre polynomial fits to the angular distributions have been made. Corresponding structures are noted in the ^{12}C(^{3}He, α_0)^{11}C reaction and comparisons are made with the α-particle core-excited threshold-state model which had been applied to ^{15}O.

[NUCLEAR REACTIONS ^{14}N(p, α_0), $E = 9.0 - 12.0$ MeV; ^{15}O deduced resonances. $\theta = 10 - 160°$, $\Delta\theta = 10°$, $\Delta E = 50$ keV.]

INTRODUCTION

Comparatively large cross sections for α-particle emission at high excitations in light compound nuclei have prompted the speculation that the structure in question is predominantly due to α clustering in the compound system and is not a manifestation of statistical fluctuations. In 1961 Wildermuth and Carovillano[1] demonstrated how the indistinguishability of the nucleons in proximate clusters can give rise to optical resonances in the decay channel in which the clusters separate. In 1969 Baz and Manko[2] summarized the properties of cluster states associated with the thresholds for the separation of the clusters.

In keeping with the scheme for cluster states described by Baz and Manko, Weller[3,4] identified structures seen in the $\alpha_0 + ^{11}$C ground-state exit channel in the ^{12}C(^{3}He, α_0)^{11}C data of Weller and Van Rinsvelt[5] and later Jackson and Weller[6] and, at lower excitations, in the ^{14}N(p, α_0)^{11}C data of Shrivastava, Boreli, and Kinsey[7] with α-particle core-excited threshold states in ^{15}O. This model pictures the ^{15}O compound nucleus as an α-particle coupled in an $l = 1$ orbital to one of the states of the ^{11}C core. The lowest lying of the resultant cluster states has an excitation associated with the threshold for α decay of the compound system. Higher excitations in ^{15}O are based on excitations of the core and different couplings of the $l = 1$ orbital angular momentum to the intrinsic angular momenta of the core. The multiplet splitting associated with the first three states of the ^{11}C core has been reported by Weller[3,4,6] with the multiplicity of the splitting confirming the $l = 1$ assignment to the orbital angular momentum of the clusters.

As mentioned above, Weller based his conclusions about the excited-core α-cluster nature of ^{15}O on the ^{14}N(p, α_0)^{11}C data[7] for the first three α-cluster levels (those corresponding to the ground state of the core) and on the ^{12}C(^{3}He, α_0)^{11}C data[3,5,6] for the higher-lying levels in ^{15}O. In extending the ^{14}N(p, α_0)^{11}C data to excitations in ^{15}O covered by the ^{12}C(^{3}He, α_0)^{11}C data, the present experiment provides the alternate entrance-channel data needed for a test of Weller's conclusions.

EXPERIMENTAL PROCEDURE

The data were taken in a 46-cm scattering chamber with an array of up to 10 50-μm-deep silicon surface-barrier detectors. Since the detectors were thin and their bias voltages were kept low, the proton pulse heights were kept below those from the ground-state α particles. At higher energies, the pulses from the ground-state ^{3}He and first-excited-state α particles could also be identified above the proton energy-loss pulses. Conventional electronics were used in conjunction with the PDP-9 computer in which the data were routed into either 128- or 256-channel spectra.

A solid target was preferred over a gas target since energy loss in the exit window of a gas cell would have shifted the α group being studied into the proton energy-loss pulses at the lower energies of interest. The targets used consisted of natural nitrogen in the form of adenine vacuum evaporated to a thickness of approximately 500 μg/cm^2 on 20-μg/cm^2 natural carbon backings. The maximum energy loss of about 500 keV to the outgoing α particles gave a resolution sufficient to separate the ground-state α group (the uppermost group in the spectrum) from the ground-state ^{3}He group at all angles and energies of interest. The beam energy loss in the target contributed to give an over-all resolution of 30 keV for the incident protons at 9.0 MeV.

Since adenine sublimates and decomposes at relatively low temperatures, the beam intensity was kept well below 10 nA. During the course of an excitation function measurement, the α intensity was periodically checked at the initial energy for that set of runs. No deterioration of the target was noted.

Absolute cross sections were obtained to a precision of 15% by comparing our $^{14}N(p, \alpha_0)^{11}C$ data with the known $^{16}O(p, p_0)^{16}O$ cross section.[8,9] This was done at a beam energy of 12 MeV and a laboratory angle of 90° using a gas cell alternately filled with natural oxygen then with natural nitrogen to $\frac{1}{4}$ atmospheric pressure. Our total cross section of 31 mb at 9 MeV is to be compared with the value of 20 mb reported by Shrivastava, Boreli, and Kinsey.[7]

DATA AND ANALYSIS

16 differential cross-section excitation functions [a few of which are shown in Fig. 1(b)] were measured every 10° at laboratory angles of 10 through 160° in steps of 50 keV covering the region of 9.0 to 12.0 MeV in beam energy, corresponding to excitations of 15.7 to 18.5 MeV in the ^{15}O compound system. The differential excitation functions were normalized to an angular distribution measured at a beam energy of 10.7 MeV using a single detector and a fixed monitor. The 61 angular distributions which resulted from the normalization were each expanded in a series of Legendre polynomials utilizing a least-squares technique. The coefficients of an eight-order fit to the data are plotted in Fig. 1(c). Below 11 MeV the seventh-

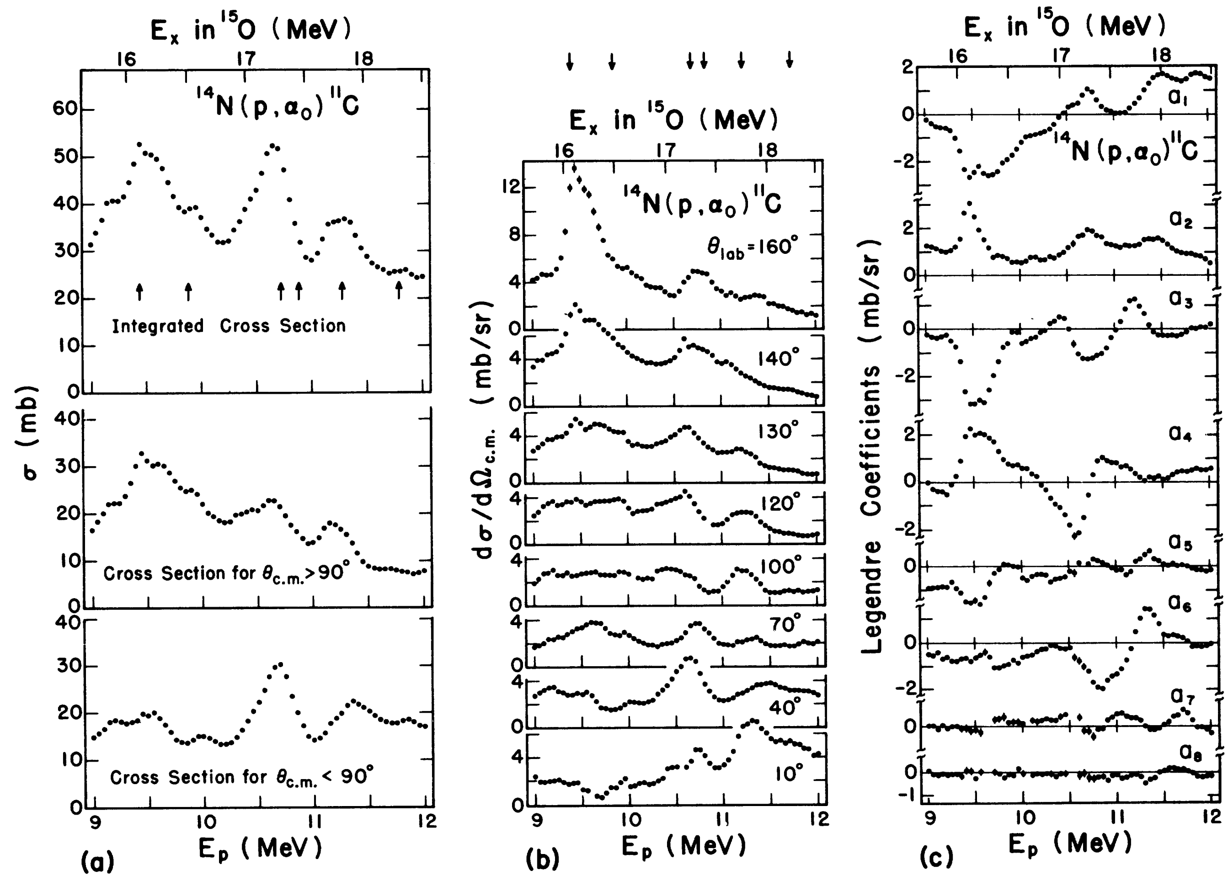

FIG. 1. Energy dependence in the reaction $^{14}N(p, \alpha_0)^{11}C$. (a) The cross section as integrated from 0 – 180°, 90 – 180°, and 0 – 90° c.m. using the Legendre polynomial fits to the data. The arrows indicate the position of cluster structures identified in the $^{12}C(^3He, \alpha_0)^{11}C$ data of Ref. 5. (b) Sample differential excitation functions. (c) The coefficients in the Legendre polynomial fits to the data. Standard deviations are shown in all cases where the error bars exceed the dimensions of the plotted point.

and eighth-order coefficients are negligible, and even above 11 MeV their magnitudes are small. Integrals over the angular distributions from 0 to 90° and from 90 to 180° were calculated from the 0- and odd-order coefficients of the Legendre polynomial fits. These along with the integrated cross section obtained from $4\pi a_0$ are plotted in Fig. 1(a) and are in excellent agreement with corresponding numerical integrations performed directly on the data using a trapezoidal rule.

A sampling of the angular distributions is shown in Fig. 2 along with the Legendre polynomial fits terminated at the sixth-order. Extension to eight orders only improves the fits in the vicinity of $E_p = 11.7$ MeV, which is expected as channels of higher angular momenta are opened. The data in their entirety are represented in the isometric plot (Fig. 3) which was drawn by computer from the Legendre coefficients of the fits through the sixth order.

RESULTS

The fluctuating cross sections and varying angular distributions demonstrate that $^{14}N(p, \alpha_0)^{11}C$ is predominantly a compound-nuclear reaction in the $E_p = 9$- to 12-MeV region of the present study. The data show three large, essentially separated structures near excitations of 16.2, 17.2, and 17.8 MeV in the ^{15}O compound system. Each of these large structures is a composite of several overlapping levels as is seen in the plot of the integrated cross section, and even more clearly in the plots separating the integrated cross section into its forward and backward components. The presence of significant odd-order coefficients in the Legendre polynomial expansions indicates the presence of partial waves of opposite parity in the reaction amplitude. This may arise from an interference of overlapping structures and/or an interference with the background.

In the first of the large structures, four substructures can be discerned. The first of these, at 15.9 MeV, is most evident in the differential cross-section excitation functions at 20 through 60°(lab), although it is also seen in the backward-angle cross-section plot. In the $^{12}C(^3He, \alpha_0)^{11}C$ data of Ref. 5, a sharp little peak is seen nearby (at 15.8 MeV). However, this peak was not included in Weller's subsequent discussions of

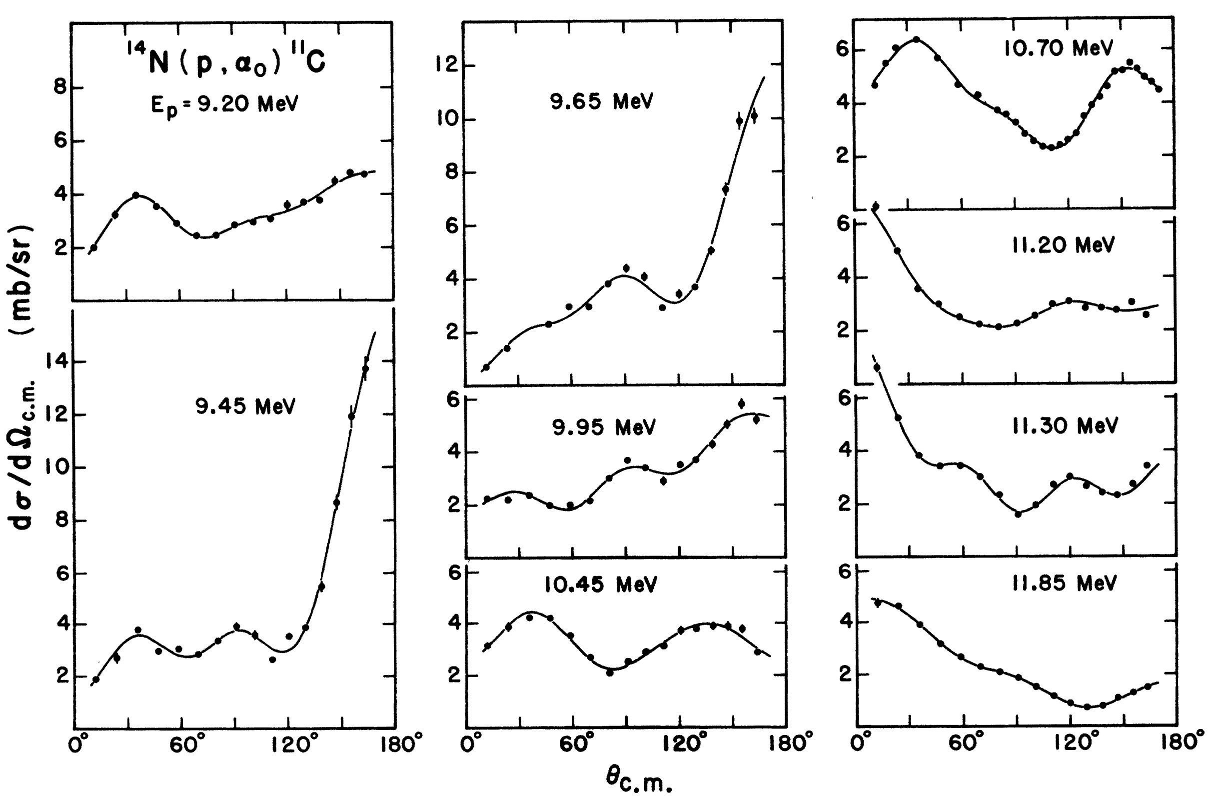

FIG. 2. Sample angular distributions for $^{14}N(p, \alpha_0)^{11}C$. The curves are generated from Legendre polynomial fits to the data terminated at the sixth order.

cluster states.[3,4] The most prominent structures in our data are the strong, backward-peaking resonances at 16.1 and 16.25 MeV. The lower lying of these levels appears sharper than its neighbor and exhibits a strongly resonant a_2 coefficient. In the ^{12}C(^{3}He, α_0)^{11}C reaction a broad structure has been observed at 16.1 MeV[5] and subsequently resolved into three peaks.[3] Weller identified these as the three positive-parity states formed by coupling an α particle to the $J^\pi = \frac{5}{2}^-$ second excited state in ^{11}C, with a relative orbital angular momentum $l = 1$ between the α particle and the ^{11}C core. This triplet [16.04, 16.09, and 16.19 MeV in ^{12}C(^{3}He, α_0)^{11}C] might be partially resolved in the two levels at 16.1 and 16.25 MeV seen in ^{14}N(p, α_0)^{11}C. The next feature in our data is a weak bump in the excitation functions at about 16.6 MeV. This too has its counterpart in the ^{12}C(^{3}He, α_0)^{11}C data of Weller and Van Rinsvelt,[5] where a reasonably large broad structure is clearly seen. In his subsequent papers, Weller[3,4] identifies this with the third excited ($J^\pi = \frac{3}{2}^-$) state of the ^{11}C core. It follows that this should also be a positive-parity triplet.

The second of the gross structures, seen in the integrated cross section and in its forward- and backward-angle components, peaks around an excitation of 17.25 MeV in ^{15}O. Closer scrutiny reveals that this is a composite of a broad structure at about 17.0 MeV underlying a sharper peak at 17.25 MeV. The differential cross-section excitation functions all reveal activity in this region, but are noticeably out of phase with each other.

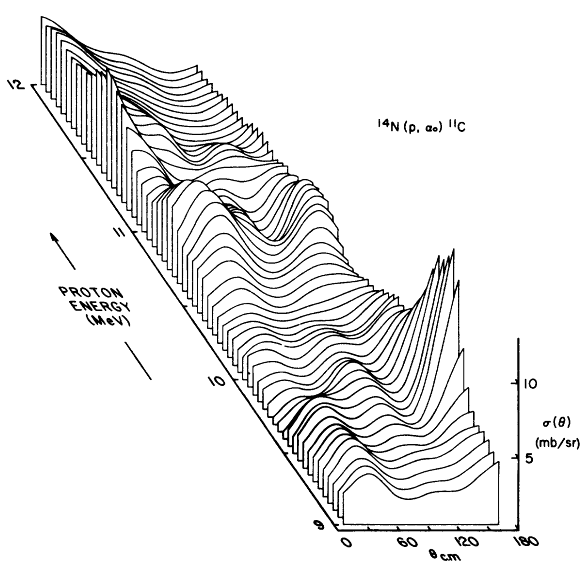

FIG. 3. An isometric plot representing the entire region of excitation in ^{14}N(p,α_0)^{11}C as generated from the sixth-order Legendre polynomial fits to the data.

The ^{12}C(^{3}He, α_0)^{11}C data[5] at 140° show two sharp peaks at 17.3 and 17.45 MeV and these positions were subsequently identified with the $J^\pi = \frac{1}{2}^+$ and $\frac{7}{2}^-$ excitations of the ^{11}C core.[3,4] Except at far backward angles in our ^{14}N(p, α_0)^{11}C data where a broad structure encompasses the excitations of both of the sharp ^{12}C(^{3}He, α_0)^{11}C peaks, no significant indication can be found in our data for a structure at 17.45 MeV. Since the coefficients in the Legendre polynomial expansions are rapidly varying through this region, they suggest the presence of several overlapping levels. Under these circumstances a level's apparent position as observed in one reaction may differ from that observed in another reaction.

The last of the gross structures appears as a plateau in the integrated ^{14}N(p, α_0)^{11}C cross section. The lower energy edge originates from a peak at 17.7 MeV in the backward-angle cross section, while the higher energy edge comes from a peak at 17.9 MeV in the forward-angle cross section. The ^{12}C(^{3}He, α_0)^{11}C data at 140° of Ref. 5 has a terrace ending where the ^{14}N(p, α_0)^{11}C plateau begins. Weller identified this position ($E_x = 17.8$ MeV) with the $J^\pi = \frac{5}{2}^+$ excitation of the ^{11}C core.

There is some evidence in the integrated cross section and in its forward-angle component for a further weak structure at 18.35 MeV. The ^{12}C(^{3}He, α_0)^{11}C data show something here too, which Weller has also correlated with a core excitation: the $J^\pi = \frac{3}{2}^+$ level in ^{11}C. The results of the present experiment are summarized in Fig. 4 which gives the excitation energies in ^{15}O corresponding to structures seen in the integrated cross section for the ^{14}N(p, α_0)^{11}C reaction. The cluster structures as identified in ^{12}C(^{3}He, α_0)^{11}C are included for comparison.[3,5]

CONCLUDING REMARKS

Besides the ^{14}N(p, α_0)^{11}C and ^{12}C(^{3}He, α_0)^{11}C reactions, consideration should be given to the alternate exit channels investigated by others. The ^{14}N(p, γ_0)^{15}O work of Kuan *et al.*[10] bears no similarity to the present ^{14}N(p, α_0)^{11}C results. However, note should be made of the ^{14}N(p, p)^{14}N elastic and inelastic scattering data of Boreli *et al.*[11] No significant structure is seen in the elastic channel between 16.2 and 18.0 MeV, although there is an indication of a structure at 16.1 MeV. In the inelastic proton channels investigated by Boreli and co-workers, evidence is seen for broad structures (about 0.5 MeV wide) near an excitation of 16.6 MeV for p_2 and near 17.3 and 17.8 MeV for both p_4 and p_6. These peaks were interpreted as probably due to intermediate

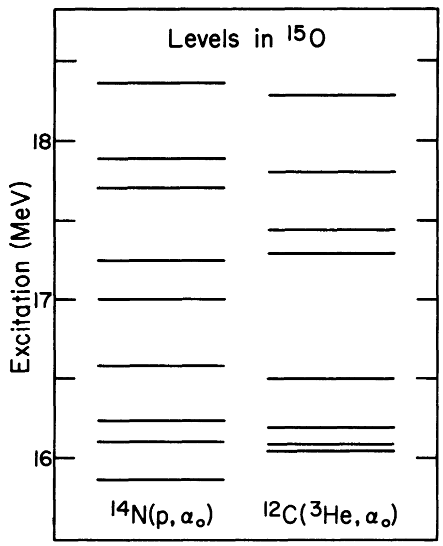

FIG. 4. Structures noted in the integrated $^{14}N(p, \alpha_0)^{11}C$ cross sections of the present study compared with the cluster structures reported for $^{12}C(^3He, \alpha_0)^{11}C$ in Ref. 3.

structure since none of them has a counterpart in the elastic channel. It is not clear how these proposed intermediate structures affect the $^{14}N(p, \alpha_0)^{11}C$ reaction.

The elastic scattering data for $^{12}C(^3He, ^3He)^{12}C$ was reported by Weller and Van Rinsvelt[5] in conjunction with their data on $^{12}C(^3He, \alpha_0)^{11}C$. Resonances at 15.9, 16.4, 17.5, and 18.0 MeV in ^{15}O were obtained from an optical-model-plus-resonance analysis of the elastic data. The 15.9- and 16.4-MeV resonances could possibly correspond to the structures at 16.1 and 16.6 in the present $^{14}N(p, \alpha_0)^{11}C$ data. However, the observed structure in the vicinity of the 17.5- and 18.0-MeV resonances is more complicated than suggested by the two-level fit to the data. As a result the correspondence to the structures seen in $^{14}N(p, \alpha_0)^{11}C$ is not clear.

Further difficulties include the interference effects of opposite-parity components in the $^{14}N(p, \alpha_0)^{11}C$ reaction amplitude. For instance, according to the α-particle core-excited threshold-state model, the members of the triplet centered around 16.1 MeV should all have the same (positive) parity. However, the strong backward peaking in the $^{14}N(p, \alpha_0)^{11}C$ data, which is naturally cause for the large coefficients of the odd-order Legendre polynomials, is evidence of the presence of negative-parity partial waves. Another problem concerns the very nature of a search for core excitations while looking only at their overlap into the ground-state α exit channel. As Baz and Manko[2] point out, higher excitations of the core should be observed in exit channels to the correspondingly higher levels in ^{11}C. This, however, would be a more difficult investigation because of the low energies of the various α groups near their thresholds. The total cross-section data of Jacobs *et al.*[12] for activation of ^{11}C in any of its energetically possible states through $^{14}N(p, \alpha)^{11}C$ provides some information concerning this point. Their data follows the basic trend of our α_0 data but with the larger cross sections expected as more α channels are included.

The results of the present $^{14}N(p, \alpha_0)^{11}C$ experiment and comparisons with the results for alternate channels indicate that further investigation is needed to sustain the identification of the α-cluster states as made by Weller. Detailed comparisons with the predictions of the α-particle core-excited threshold-state model would require definitive spin and parity assignments for the levels in ^{15}O. This becomes progressively more difficult for higher excitations as the number of overlapping levels increases.

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