where now we have further simplified the notation, namely,

$$w_{j1}\equiv w_{j1}(1,2,3), \quad w_{j1}'\equiv w_{j1}(1',2',3'), \quad \text{etc.}$$

Since the asterisks have been dropped, the last two terms in (46) are seen to cancel by virtue of (41). Therefore, comparing (46) and (40a), $R_{ej}=\frac{1}{2}R_{oj}$. To seal the proof we should point out that when Eqs. (43) and (44) represent the permutations (123) and (132), respectively, the matrices representing (12), (13), and (23) are, respectively,

$$\begin{pmatrix} 0 & 1 \\ 1 & 0 \end{pmatrix}, \quad -\frac{1}{2}\begin{pmatrix} \sqrt{3} & 1 \\ 1 & -\sqrt{3} \end{pmatrix}, \quad -\frac{1}{2}\begin{pmatrix} -\sqrt{3} & 1 \\ 1 & \sqrt{3} \end{pmatrix}. \tag{47}$$

The matrices (47) and (44) cannot be brought simultaneously to diagonal form. Thus, the properties ascribed to w_{j1}, w_{j2}, leading ultimately to $R_{oj}=2R_{ej}$, were indeed those appropriate to the irreducible two-dimensional representation of π_3.

PHYSICAL REVIEW VOLUME 127, NUMBER 6 SEPTEMBER 15, 1962

Nuclear Energy Levels of C^{13}; Two-Stage Reaction $N^{14}(t,n)O^{16*}(\alpha)C^{12}$†

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(Received May 4, 1962)

Alpha spectra from the triton bombardment of natural nitrogen were studied at laboratory angles of 30 and 90° with a double-focusing magnetic spectrometer. Observation of alpha groups from $N^{14}(t,\alpha)C^{13}$ allowed the positions of energy levels in C^{13} to be investigated up to an excitation energy of 12.5 MeV. In addition to previously well-determined levels at lower excitations, levels were observed at 10.736, 10.809, 11.000, 11.078, 11.721, and 12.131 Mev. Standard deviations in these values ranged from 0.020 to 0.030 MeV. Previously reported levels at 5.51, 6.10, and 10.47 MeV were not seen. Certain structural features of the alpha continuum underlying C^{13} groups could be tentatively identified with alpha groups from the two-stage reaction $N^{14}(t,n)O^{16*}(\alpha)C^{12}$ proceeding through known levels in O^{16} near 15-MeV excitation. Cross sections are reported for various features of the alpha spectra as well as for corresponding features of the proton spectra.

I. INTRODUCTION

THE present experiment was primarily concerned with a study of the alpha-particle spectra produced by the bombardment of N^{14} with 1.8- to 2.6-MeV tritons. These alpha particles could be attributed to five nuclear reactions:

$$N^{14}(t,\alpha)C^{13}, \qquad Q_0=12.263 \text{ MeV}; \tag{1}$$

$$N^{14}(t,n\alpha)C^{12}, \qquad Q_0=7.316 \text{ MeV}; \tag{2}$$

$$N^{14}(t,n)O^{16*}(\alpha)C^{12}, \qquad Q_0=7.316 \text{ MeV}; \tag{3}$$

$$N^{14}(t,C^{12})He^5(\alpha)n, \qquad Q_0=7.316 \text{ MeV}; \tag{4}$$

$$N^{14}(t,2\alpha)Be^9, \qquad Q_0=1.612 \text{ MeV}. \tag{5}$$

The energetic relations between the nuclei involved are summarized in Fig. 1.

Alphas from reaction (1) were emitted with discrete energies corresponding to the energy levels of the residual nucleus, C^{13}. This experiment provided an opportunity of studying C^{13} levels with good resolution up to an excitation of 12.5 MeV. Energy levels in this region of excitation are discussed in Sec. III A.

Underlying the particle groups from reaction (1) was a continuous energy distribution of alpha particles from low energies to a maximum energy determined by the Q value of reaction (2). These alphas were associated with the three-body breakup reaction in which an alpha particle, a neutron, and a C^{12} nucleus were produced "simultaneously." In this case, the alpha spectrum at a given laboratory angle was determined by the angular correlations of the three emerging particles.

Another possible source of alpha particles was reaction (3), which differed from reaction (2) in that it involved two, two-body breakup reactions in series,

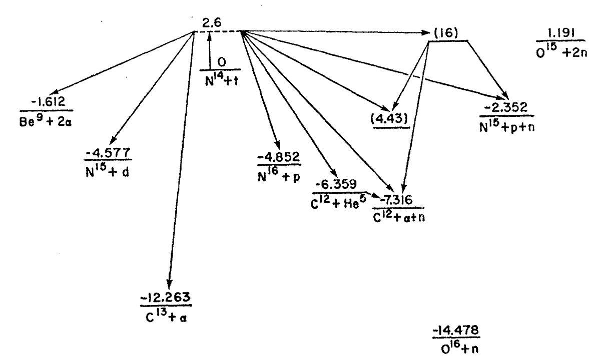

FIG. 1. Some energetic relations in the $N^{14}+t$ system. Energies are in MeV. Those without parentheses are relative to $N^{14}+t$; those in parentheses are energies of excitation in the nuclei with which they are associated. Arrows represent transitions of concern in the present experiment.

† Work performed under the auspices of the U. S. Atomic Energy Commission

with the formation of an intermediate nucleus (O^{16}) in a definite state of excitation. Here, the neutrons in the first stage of the reaction would be emitted with discrete energies, corresponding to the various excited states in O^{16}, while the alpha-particle energies in the second stage would be determined both by the Q value of $O^{16*}(\alpha)C^{12}$ and by the velocity of the O^{16*} nucleus at the instant of alpha emission. The alpha particles observed at a given angle, associated with a single level in O^{16}, would have a considerable spread in energy because the O^{16*} nuclei were recoiling in a wide range of angles, with a corresponding range of energies, following the emission of a neutron in the first stage of the reaction.

Reaction (4) was analogous to reaction (3) in that alphas were emitted in the second stage of a two-stage process. In this case, the intermediate nucleus, He^5 in the ground state, was light and had a low Q value for alpha emission in contrast to O^{16*} which was heavy and had a high Q value for alpha emission. These differences made the expected energy distribution from reaction (4) differ markedly from that from reaction (3). Considering only the broad ($\Gamma = 550$ keV) ground state of He^5 and the ground and first excited states of C^{12} led to the prediction of four broad alpha groups associated with reaction (4). Two groups were associated with each set of levels, corresponding to alphas emitted forward and backward in the He^5 center-of-mass system. None of these predicted groups could be distinguished in the spectra. The 3-MeV broad first excited state of He^5 was not considered because of its extreme width.

TABLE I. Energy levels of C^{13}. Levels correspond to alpha-particle groups from $N^{14}(t,\alpha)C^{13}$, observed at a laboratory angle of 30°. Quoted widths in the present experiment have had an instrumental width of 65 keV unfolded from them.

Compilation[a] Excitation energy (MeV)	Level width (keV)	Present experiment Excitation energy (MeV)	Level width (keV)
3.085±0.005		b	
3.680±0.007		b	
3.850±0.010		b	
5.51 ±0.05		c	
6.10 ±0.05		c	
6.868±0.006	6	b	e
7.498±0.007	<5	b,d	
7.553±0.007	<5		
7.680±0.015	75±15	b	
8.33 ±0.1	1000±250	c	
8.85 ±0.03	175±50	8.860±0.020	145±20
9.509±0.008	<10	f	e
9.897±0.010	<10	f	e
10.47 ±0.04	200	c	
		10.736±0.020	e
10.80 ±0.03	120	10.809±0.020	e
11.02 ±0.02	50	11.000±0.020	e
11.08 ±0.03	<80	11.078±0.020	e
11.97 ±0.015	70	11.721±0.030	125±20
12.07 ±0.03	broad		
12.18 ±0.03	~150	12.131±0.030	125±30
12.44 ±0.03	~160	c	

[a] Reference 3.
[b] Observed, but not measured.
[c] Not observed in the present experiment.
[d] Not resolved.
[e] The instrumental width was dominant; level widths are estimated to be <30 keV.
[f] Used as energy references.

The low Q value of reaction (5) restricted alphas from this reaction to rather low energies. A continuous alpha distribution would be expected below the energetic end point. No increase was observed in the continuum below this point; this reaction will not be considered further.

The alpha spectra would then be expected to have three, more or less distinct, features corresponding to the four reactions: (1) narrow groups of Gaussian shape, (2) a continuum, and (3) and (4) broad groups. This classification represents a limiting case of the actual situation since the distinction between (2) and (3) becomes more difficult, both experimentally and in principle, when the O^{16} level under consideration in (3) is very broad and therefore short-lived. In a similar manner the distinction between (1) and (2) tends to disappear when the C^{13} level in (1) is a short-lived, broad neutron-emitting state so that reaction (1) becomes $N^{14}(t,\alpha)C^{13*}(n)C^{12}$.

For experimental purposes, an important property of the alphas from reaction (3) as opposed to those from reactions (1), (2), and (4) was the dependence of alpha-particle energy on triton bombarding energy. Whereas the energies of alphas from reactions (1), (2), and (4) were quite dependent on the triton energy, the energies of alphas from reaction (3) were dependent on triton energy only indirectly, through their dependence on the O^{16*} recoil energy. Therefore, it was possible to distinguish particle groups associated with (3) from groups associated with (1) and (4) by their nearly complete independence of triton energy.

The possibility of observing the results of two-stage reactions in the triton bombardment of N^{14} was noted during a study of the proton spectra in which anomalous broad, flat-topped groups were seen.[1] The reactions involved were analogous to those described above, with the alpha particle in each instance being replaced by a proton. For the proton spectra it was possible to associate two prominent broad groups with the proton decay of two known levels in O^{16}. A similar attempt has been made in the analysis of the present experiment.

II. EXPERIMENTAL

Charged particles produced by the bombardment of natural nitrogen with tritons were analyzed with a 16-in. radius, double-focusing magnetic spectrometer at laboratory angles of 30 and 90° to the triton beam. The tritons, accelerated to a maximum energy of 2.8 MeV by a Van de Graaff generator, bombarded a gas target of nitrogen. A CsI scintillation counter was used as the charged-particle detector at the spectrometer exit. The

[1] M. G. Silbert, N. Jarmie, and D. B. Smith, Nuclear Phys. **25**, 438 (1961); N. Jarmie, M. G. Silbert, and D. B. Smith, *ibid.* **25**, 443 (1961).

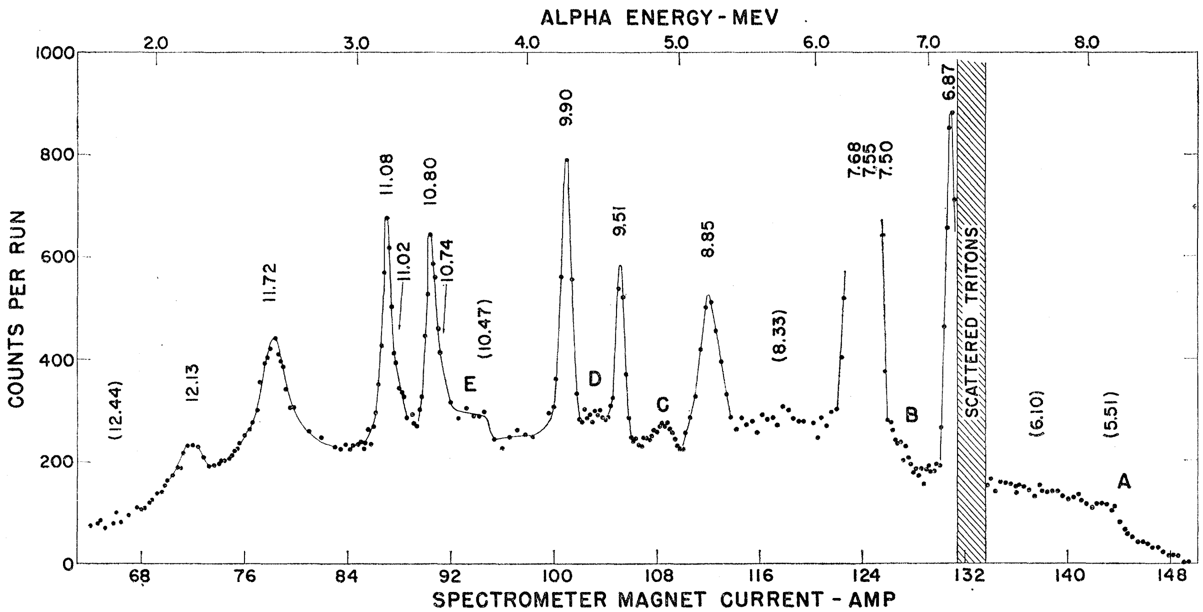

FIG. 2. Alpha spectrum at 30° (lab) from the bombardment of natural nitrogen with 2.6-MeV tritons. Peaks associated with energy levels in C^{13} are labeled with the excitation energies in MeV. Parentheses denote the calculated positions of peaks which were not observed (see text). Letters *A* through *E* label features which have been attributed to the two-stage process $N^{14}(t,n)O^{16*}(\alpha)C^{12}$ on the basis of their independence of triton energy. In this and subsequent figures the statistical reliability of the points is greater than is indicated by the number of counts per run and can be estimated from the scatter. The number of counts per run in all of the figures has been normalized to the same triton beam current integral.

experimental details have been discussed in previous reports.[1,2]

Several samples of the nitrogen target gas were mass-spectrometrically analyzed during the course of the experiment. The N^{14} content was always greater than 99 at.%; contaminants such as C^{12}, O^{16}, and Ne^{20} were each present in amounts less than 0.1 at.%. On the basis of previous experience with methane, oxygen, and neon targets, no alpha groups in the spectra could be assigned to these contaminants.

Three deuteron groups were identified near 88 amperes on the spectrometer scale in Fig. 2. They have been deleted for clarity; no confusion with nearby alpha groups was possible. Identification as deuterons was possible since these groups disappeared when a CsI crystal, thin enough to allow deuterons of this energy (1.65 MeV) to pass through, was substituted for a thicker crystal at the spectrometer exit. The energies of the three groups agreed well with expected values for deuterons elastically scattered from N^{14} (HD^+ ions were present in small amounts in the T^+ beam) and from $N^{14}(t,d)N^{15}$ (first and second excited states).

III. RESULTS AND DISCUSSION

Alpha-particle spectra from $N^{14}+t$, for a range of triton energies from 1.8 to 2.6 MeV at the center of the target, are presented in Figs. 2 to 7. The majority of these spectra were obtained at a laboratory angle of 30° in an effort to distinguish certain features of the alpha continuum by varying the triton energy. Both alpha-particle and proton spectra were also studied at 90° for comparison with the results at 30°.

A. C^{13}

The present experiment afforded an opportunity to study the positions of the energy levels of C^{13} from the first excited state at 3.09 MeV to about 12.5-MeV excitation. The Q value for $N^{14}(t,\alpha)C^{13}$ is 12.263 MeV, high enough so that the ground-state group was beyond the range of the magnetic spectrometer. Observation of particle groups corresponding to C^{13} levels was made more difficult by the alpha-particle continuum, which extended from low particle energies to a point equivalent to an excitation of 4.95 MeV in C^{13}. It was possible to distinguish between C^{13} groups and two-stage structure in the continuum by observing the shift in alpha energy with changes in triton bombarding energy, as explained in the Introduction. As in previous experiments,[1,2] the combination of momentum analysis in the magnetic spectrometer followed by detection in CsI provided complete separation between alpha particles and protons.

The results of the present experiment, pertaining to the energy levels of C^{13}, are presented in Table I and compared to the compilation of Ajzenberg-Selove and Lauritsen.[3] Significant differences between previously

[2] N. Jarmie and M. G. Silbert, Phys. Rev. **120**, 914 (1960); M. G. Silbert and N. Jarmie, *ibid*, **123**, 221 (1961).

[3] F. Ajzenberg-Selove and T. Lauritsen in *Energy Levels of Nuclei: A=5 to A=257* (Springer-Verlag, Berlin, 1961); Landolt-Börnstein, New Series, Group 1: Nuclear Physics and Technology, Vol. I.

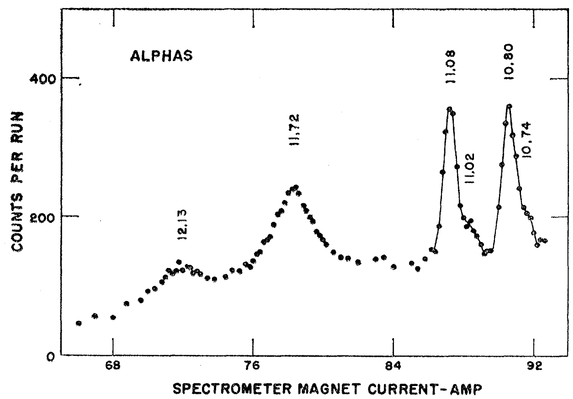

FIG. 3. High resolution alpha spectrum taken at 30° (lab) with 2.6-Mev tritons. Resolution has been increased by a factor of 1.8 over that in Fig. 2 in order to study the poorly resolved levels (10.74 and 11.02) in greater detail. The peaks labeled 11.72 and 12.13 were repeated with high resolution and good statistics to verify their positions.

reported levels and those reported here are summarized below.

No attempt was made to determine the Q values of the well-known levels at 3.09, 3.68, 3.85, 6.87, 7.50, 7.55, 7.68, 9.51, and 9.90 MeV, although the corresponding alpha groups were observed. The 9.509±0.008- and 9.897±0.010-MeV levels were used in determining the spectrometer energy scale. Levels at 8.85, 10.80, 11.02, and 11.08 MeV were confirmed. A new level, barely resolved from that at 10.809 MeV, was evident at 10.736 MeV. The level reported here at 11.721 MeV is presumably the level previously reported to be at 11.97 MeV. Rather than two levels at 12.07 and 12.18 MeV, a single level was seen at 12.13 MeV. The 12.44-MeV level was not evident but would be expected to be small and could have been obscured by the continuum and by background. Levels previously reported at 5.51, 6.10, 8.33, and 10.47 MeV were not observed. A broad ($\Gamma = 1000$ keV) level at 8.33 MeV could easily have been obscured by the alpha continuum; the spectra reveal a possible maximum in this region and the failure to observe such a group is not considered significant. Although the levels may have been weakly excited and these groups obscured by the continuum, the absence of groups corresponding to levels at 5.51-, 6.10-, and 10.47-MeV excitation, combined with the lack of other supporting evidence for these levels, casts doubt on their existence.

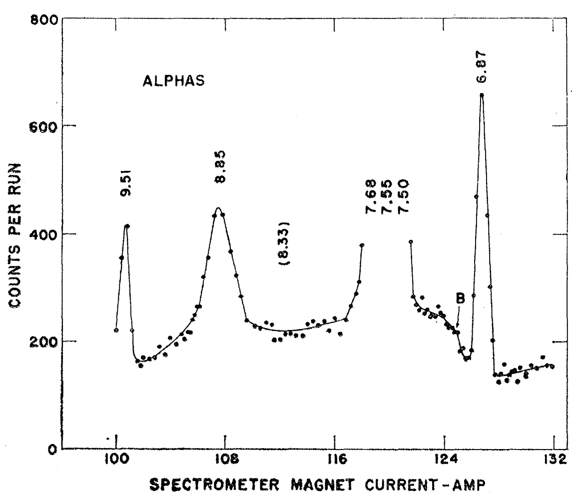

FIG. 4. Alpha spectrum from $N^{14}+t$ at 30° (lab) with 2.2-MeV tritons. At this bombarding energy the feature B is clearly exposed. Note the sharp high-energy edge in contrast to that expected from a broad C^{13} level.

The nuclear energy levels of C^{13} in the region of interest have been studied previously, with C^{13} as the residual nucleus, by means of the reactions $C^{12}(d,p)C^{13}$ and $B^{11}(He^3,p)C^{13}$ and, with C^{13} as the compound nucleus, by means of the reactions $Be^9(\alpha,n)C^{12}$ and $C^{12}(n,n)C^{12}$. The discussion below will be limited to those levels for which the present experiment provided additional information.

5.51- and 6.10-MeV levels. Assignment of these levels to C^{13} was made on the basis of the work of Moak *et al.*[4] with $B^{11}(He^3,p)C^{13}$. They employed a NaI charged-particle spectrometer and detected two small proton groups which were interpreted as C^{13} levels. These particle groups were superimposed on the proton continuum from $B^{11}(He^3,pn)C^{12}$, quite near to the end point of the continuum, which was equivalent to an excitation of 4.95 MeV in C^{13}. The two groups appeared in spectra taken at both 13 and 135° to the He^3 beam and were shown to be protons by absorber measurements. Considerable effort was made to prove that the peaks were not due to target contaminants.

The possibility was suggested by Moak *et al.* that the group corresponding to a 5.51-MeV level could be associated with the three-body breakup spectrum. However, a calculation by them, based on K. M. Watson's analysis of the three-body breakup problem, failed to fit their experimental spectrum near the continuum end point.

In the light of our observations of structure from two-stage processes superimposed on the continua from three-body breakup, it seems possible that the rather poorly-defined groups observed by Moak *et al.* were due to the two-stage process $B^{11}(He^3,n)N^{13*}(p)C^{12}$. The excitation of the intermediate states in N^{13} would need to be about 10.2 MeV, a region in which the level structure is nearly unknown. Rough calculations for $B^{11}(He^3,n)N^{13*}(p)C^{12}$, using an intermediate level at 10.0 MeV in N^{13}, indicate that proton groups from that process would shift in energy with a change in angle of observation by about the same amount as groups from $B^{11}(He^3,p)C^{13}$. This behavior with change in angle has been noted in our observations on $N^{14}(t,n)O^{16*}(p)N^{15}$ at 30 and 90° (Figs. 8 and 9 and reference 1) and is in agreement with calculations for the latter reaction.

[4] C. D. Moak, A. Galonsky, R. L. Traughber, and C. M. Jones, Phys. Rev. **110**, 1369 (1958).

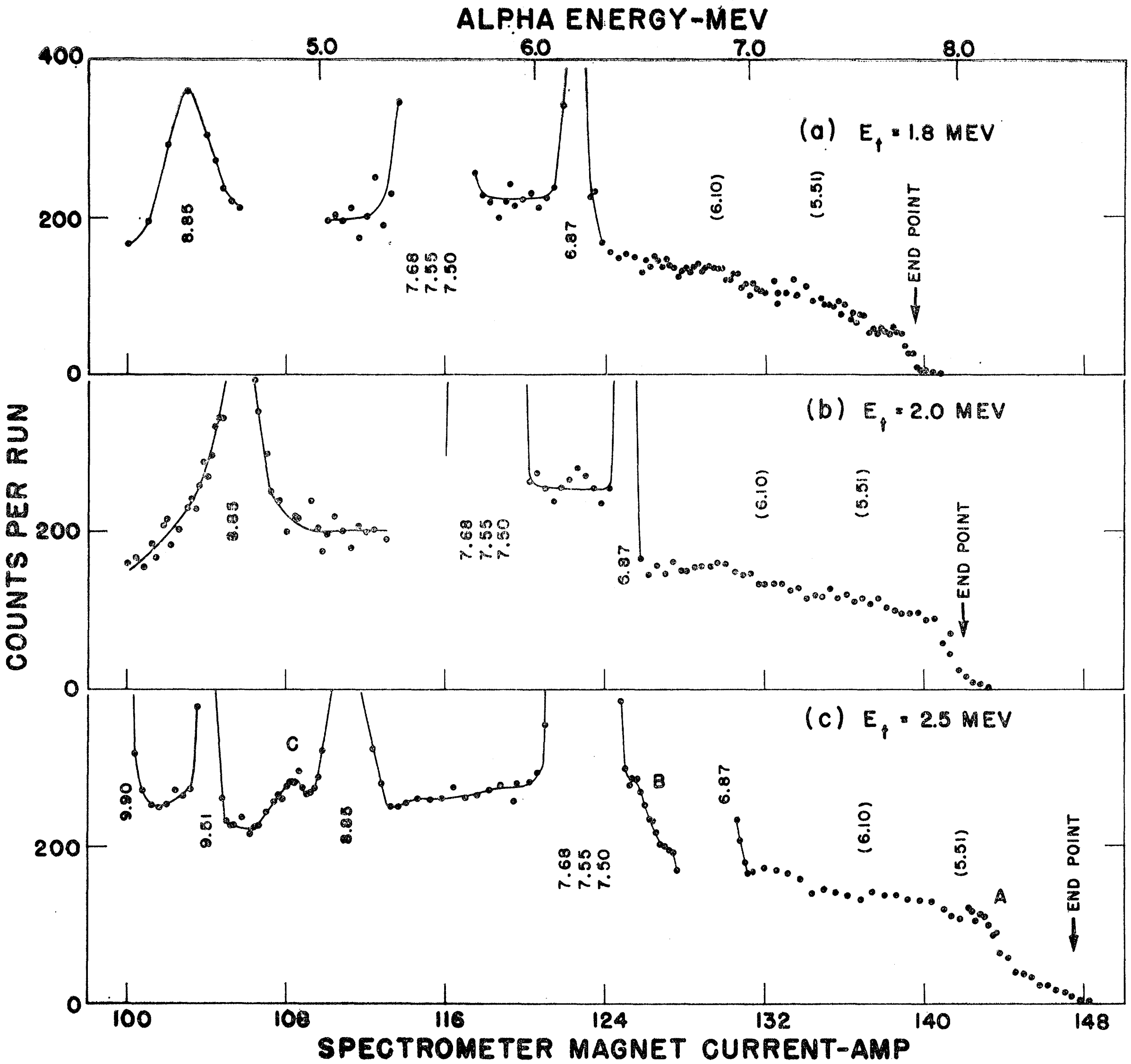

FIG. 5. Alpha spectra at 30° (lab) from the bombardment of nitrogen with (a) 1.8-MeV, (b) 2.0-MeV, and (c) 2.5-MeV tritons. The calculated positions of C^{13} levels at 5.51 and 6.10 MeV are indicated. The features *B* and *C* can be seen in (c). The shape of the alpha continuum near the energetic end point is of particular interest. (See also Fig. 2.) In (c) the continuum increases slowly below the end point, then rises abruptly at *A*. In (a) and (b) the rapid increase immediately below the end point is presumably part of the alpha group associated with *A* which has been cut off by the limitation on energy (see Fig. 7).

Experiments in which levels at 5.51 and 6.10 MeV could have been observed were carried out by Green and Middleton,[5] Young *et al.*,[6] and Huddleston *et al.*[7] In particular, Huddleston *et al.* made a specific search for corresponding resonances in the C^{12} total neutron cross section, with negative results, and were able to put upper limits on the widths of these levels. Green and Middleton, using the reaction $C^{12}(d,p)C^{13}$ in conjunction with a magnetic spectrograph, searched to an excitation of 6.8 MeV in C^{13} but observed no levels between that at 3.85 and 6.8 MeV. Young *et al.* employed the same reaction as Moak *et al.*, $B^{11}(He^3,p)C^{13}$, but attained better resolution with a magnetic spectrograph. They searched the region of interest with negative results and placed an upper limit for the cross sections of possible levels at 5.51 and 6.10 MeV at less than 10% of that at 6.87 MeV. It should be noted, however, that the groups seen by Moak *et al.* were smaller than this limit.

Turning now to the evidence of the present experiment, the situation is in a sense similar to that with $B^{11}(He^3,p)C^{13}$ in that a particle continuum extends to

[5] T. S. Green and R. Middleton, Proc. Phys. Soc. (London) **A69**, 28 (1956).
[6] T. E. Young, G. C. Phillips, R. R. Spencer, and D. A. A. S. N. Rao, Phys. Rev. **116**, 962 (1959).
[7] C. M. Huddleston, R. O. Lane, L. L. Lee, Jr., and F. P. Mooring, Phys. Rev. **117**, 1055 (1960).

the equivalent of the binding energy of a neutron in C^{13}. Particle groups corresponding to levels at 5.51 and 6.10 MeV would be superimposed on this continuum and consequently could be more easily missed if small. This region of the spectrum was searched carefully, with good statistical accuracy, with negative results. Upper limits of the cross sections at 30° (lab) for $N^{14}(t,\alpha)C^{13}$ leading to narrow levels near 5.5- and 6.1-MeV excitation can be placed at 5% of the cross section to the 6.87-MeV level. In spectra taken with 2.5- and 2.6-MeV tritons, 5.5-MeV excitation in C^{13} corresponded to an edge of the structure in the alpha continuum which was interpreted as being due to $N^{14}(t,n)O^{16*}(\alpha)C^{12}$ and which could have been mistaken for a C^{13} level. In the spectra taken with 1.8- and 2.0-MeV tritons, however, the point corresponding to 5.5-MeV excitation in C^{13} had moved relative to the continuum structure so that a more stringent upper limit could be set for the cross section for a 5.5-MeV state.

8.33-MeV level. This level was not definitely observed in the present experiment but its width is so large that it could easily have been obscured by the continuum. Its existence is supported by the work of McGruer *et al.*[8] with $C^{12}(d,p)C^{13}$ and by a broad resonance in the neutron elastic scattering and total cross sections of C^{12}.

10.47-MeV level. Evidence for a level at 10.47 MeV was presented by Hall and Bonner[9] who observed a small resonance corresponding to this excitation in C^{13} in the 4.43-MeV gamma-ray yield from $C^{12}(n,n'\gamma)C^{12}$. This level could have been, but was not, seen by McGruer *et al.*[8] with $C^{12}(d,p)C^{13}$, or in the neutron total cross section of C^{12}, in particular in the recent high resolution experiment of Fossan *et al.*[10] In the present experiment, the search for a level near 10.47-MeV excitation was complicated by the presence of a broad, sharp-edged group (E) of the type that has been attributed to the two-stage reaction $N^{14}(t,n)O^{16*}(\alpha)C^{12}$. In comparing runs with 2.4- and 2.6-MeV tritons, a C^{13} level would have shifted in relation to the broad group, which was nearly independent of triton energy. No evidence for a level near 10.47 MeV in C^{13} was seen and an upper limit for the cross section at 30° (lab) to such a level can be set at 25% of the cross section to the rather weakly excited level at 10.74 MeV.

10.74- and 10.81-MeV levels. There have been several reports of a C^{13} level near 10.8 MeV. A level at 10.759 ±0.020 MeV, with an experimental width which appeared to be less than 100 keV, was observed by McGruer *et al.*[8] Hall and Bonner[9] reported a level at 10.81 MeV, with a width of 120 keV, from their study of $C^{12}(n,n'\gamma_{4.43})C^{12}$. The C^{12} neutron total cross-section measurements also indicated such a level, which was determined by Fossan *et al.*[10] to be at 10.74 MeV and to have a width of 65 keV. The present experiment showed a prominent alpha group corresponding to an excitation of 10.809±0.020 MeV, with a weakly-excited, poorly resolved group on its high-energy side at an excitation of 10.736±0.020 MeV. The level separation could be determined with a greater precision than the excitation energies and was 73±10 keV. The observed level widths were about equal to the instrumental width and the inherent widths are therefore estimated to be less than 30 keV.

11.02- and 11.08-MeV levels. The presence of two levels at this excitation has been indicated by resonances in $Be^9(\alpha,n)C^{12}$, in $C^{12}(n,n'\gamma_{4.43})C^{12}$, and in the C^{12} neutron total cross section. The present experiment confirms the previous results. A strong alpha group was observed at an excitation energy of 11.078±0.020 MeV with a poorly resolved, weakly-excited group on its high-energy side at an excitation of 11.000±0.020 MeV. The level separation was measured to be 78±10 keV and the observed level widths were about equal to the instrumental width.

11.97-MeV level. There has been disagreement in reports of the position of the level in C^{13} in the vicinity of 11.9 MeV. Several experiments[11–14] have shown a prominent resonance in both the neutron and gamma-ray yields from $Be^9(\alpha,n)C^{12}$ at an alpha-particle energy of 1.90 MeV. The reported resonance energies agree well with each other; the most precise value is given by Tanner[13] to be 1.905±0.010 MeV, corresponding to E_x=11.97 MeV. These resonance energies have not been corrected for the distortion of the rather broad resonance by the Coulomb barrier, which would be expected to shift the apparent peak to a higher alpha energy, i.e., a higher excitation energy for the C^{13} level.

Hall and Bonner[9] obtained a value of 11.87 MeV from a study of $C^{12}(n,n'\gamma_{4.43})C^{12}$ and of the C^{12} neutron total cross section, while Fossan *et al.*[10] determined the resonance in the latter cross section to be at the equivalent of about 11.8 MeV in C^{13}. There was some uncertainty in measuring the position of this broad resonance in the $C^{12}+n$ experiments because of overlap of the next broad resonance some 300 keV higher in neutron energy. All of the experiments above in which the level width was estimated were in good agreement and placed this width at 180 to 260 keV.

The present experiment allowed this region of excitation to be searched with good resolution but was hindered by the presence of the alpha-particle continuum. A broad, prominent alpha group was observed corresponding to an excitation of 11.721±0.030 MeV in C^{13}, some 150 to 250 keV below previous values. The Coulomb barrier for alpha emission would be expected

[8] J. N. McGruer, E. K. Warburton, and R. S. Bender, Phys. Rev. **100**, 235 (1955).
[9] H. E. Hall and T. W. Bonner, Nuclear Phys. **14**, 295 (1959).
[10] D. B. Fossan, R. L. Walter, W. E. Wilson, and H. H. Barschall, Phys. Rev. **123**, 209 (1961).
[11] F. L. Talbott and N. P. Heydenburg, Phys. Rev. **90**, 186 (1953).
[12] R. E. Trumble, Jr., Phys. Rev. **94**, 748A (1954).
[13] N. W. Tanner, Proc. Phys. Soc. (London) **A68**, 1195 (1955).
[14] T. W. Bonner, A. A. Kraus, Jr., J. B. Marion, and J. P. Schiffer, Phys. Rev. **102**, 1348 (1956).

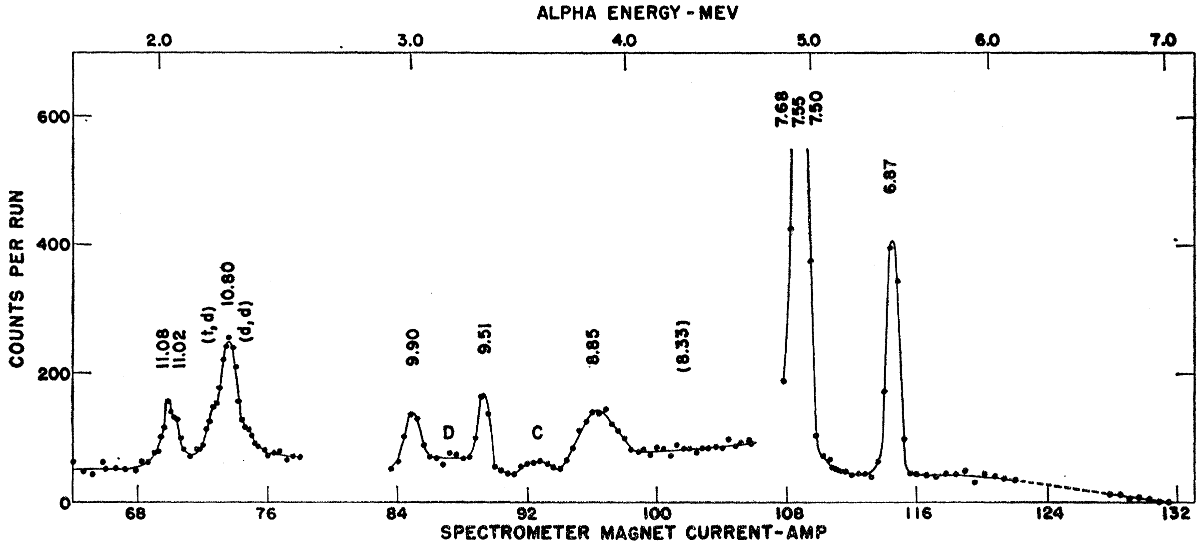

FIG. 6. Alpha spectrum at 90° (lab) from the bombardment of nitrogen with 2.6-MeV tritons. Particle groups on the low- and high-energy sides of the C^{13} 10.80-MeV group are deuterons from $N^{14}(t,d)N^{15}$ and $N^{14}(d,d)N^{14}$ as indicated. This partial spectrum is of interest primarily in showing the shape and size of the alpha continuum.

to have an effect the reverse of that for $Be^9(\alpha,n)C^{12}$, that is, to shift the peak to a higher alpha energy or lower C^{13} excitation energy. Some estimate of this Coulomb shift could be made by assuming that the continuum would be flat in this region in the absence of the Coulomb barrier. This correction, which has not been applied to the quoted value, would then be less than 30 keV. There remains an unexplained discrepancy between previous results and that of the present experiment. The present level width, 125±20 keV, is somewhat less than that determined by previous experiments.

12.07- and 12.18-MeV levels. There is good evidence for a level in this region of excitation in C^{13}; the evidence for two levels is weak. The only experiment in which levels both at about 12.07 and 12.18 MeV may have been seen is that of Risser, Price, and Class[15] on resonances in the ground-state group neutron yield from $Be^9(\alpha,n)C^{12}$. Other experiments have shown a single level which has been reported to be at from 12.08- to 12.24-MeV excitation. Bonner *et al.*[14] reported a value of 12.24 MeV ($\Gamma=200$ keV) from the neutron yield from $Be^9(\alpha,n)C^{12}$, in good agreement with the value 12.20 MeV determined by Trumble[12] with the same reaction. A somewhat lower value of 12.16 MeV ($\Gamma=180$ keV) was obtained by Hall and Bonner[9] with the reaction $C^{12}(n,n'\gamma_{4.43})C^{12}$. Several different values have been reported for this resonance in the neutron total cross section. The paper by Fossan *et al.*[10] gives a value of 12.08 MeV ($\Gamma=200$ keV) for this C^{13} level and includes a comparison of previous work.

In the present experiment a single, broad alpha group was observed, corresponding to 12.131±0.030 MeV in C^{13} ($\Gamma=125\pm20$ keV). As in the case of the 11.97-MeV level, the Coulomb barrier would be expected to shift the apparent peak to higher excitation values for $Be^9(\alpha,n)C^{12}$ and to lower excitation values for this reaction, $N^{14}(t,\alpha)C^{13}$. The correction would again appear to be less than 30 keV and has not been applied. It is possible that a broad level at 12.07 MeV might have been missed.

12.44-MeV level. A level near 12.44-MeV excitation in C^{13} was indicated by all of the experiments on $Be^9(\alpha,n)C^{12}$ in which this region was searched. Additional evidence for such a level comes from resonances in the gamma-ray yield[9] from $C^{12}(n,n'\gamma_{4.43})C^{12}$ and in the neutron total cross section.[10] The reported level position ranged from 12.4 to 12.46 MeV; the reported level width ranged from 150 to 300 keV. In the present experiment this level would be expected at 66 A in Fig. 2. Failure to observe such a level is not considered significant because emission of alpha particles of such low energy was inhibited by the Coulomb barrier of the compound nucleus and because instrumental background, which set a lower limit on the energy of the alphas that could be observed, was becoming serious in this region. A similar, rather sharp cutoff has been previously seen in the alpha spectra from the triton bombardment of oxygen and neon.

B. $N^{14}(t,n)O^{16*}(\alpha)C^{12}$

Interest in the alpha-particle continuum from $N^{14}+t$ was centered on the possibility of observing alphas from the decay of highly excited (~15 MeV) states of O^{16} produced by the reaction $N^{14}(t,n)O^{16*}$. The maximum energy of the incident triton beam corresponded to an excitation in O^{16} of 16.3 MeV. Decay of O^{16} levels at this excitation was energetically possible to the ground,

[15] J. R. Risser, J. E. Price, and C. M. Class, Phys. Rev. **105**, 1288 (1957).

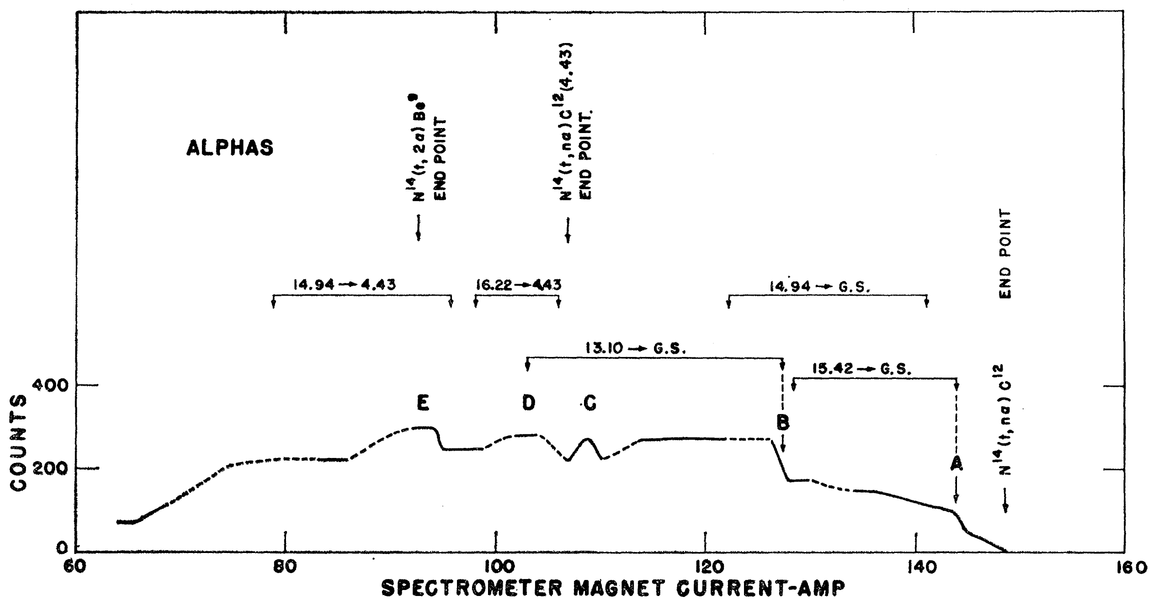

FIG. 7. Alpha continuum at 30° (lab) from the bombardment of nitrogen with 2.6-Mev tritons. This spectrum was derived from Fig. 2 by deleting the groups attributed to $N^{14}(t,\alpha)C^{13}$ and interpolating arbitrarily. The connected arrows show the calculated energy limits of the alpha groups from $N^{14}(t,n)O^{16*}(\alpha)C^{12}$ for the specified sets of levels in O^{16} and C^{12} (O^{16} level → C^{12} level). The energetic end points for the three-body breakup processes are also indicated.

4.43-, and 7.66-MeV states in C^{12} but the alpha particles associated with the latter transition would have been emitted with energies too low to be detected in the present experiment.

Only those states of O^{16} with "natural" parity, that is, parity $(-1)^J$, can decay by alpha emission to the 0^+ ground state of C^{12}. This restriction reduced the number of possible alpha groups involved in the ground-state transition. No such simplification is possible in the decay to the 2^+ level at 4.43 MeV in C^{12}. In the higher energy part of the continuum, where only C^{12} ground-state transitions could be involved in the two-stage process, an attempt was made to associate structure in the spectra with particular O^{16} states. Lower energy alphas could have resulted from decay to either the ground or first excited state of C^{12} and it was not possible to identify features in the continuum with specific O^{16} states.

Figure 7 shows the alpha-particle continuum from $N^{14}+t$, with the narrow groups attributed to C^{13} levels deleted for clarity. Connected arrows indicate the calculated energetic limits of alpha particles from the decay of particular known levels[3] in O^{16} to the ground or 4.43-MeV state of C^{12}. Calculations for the ground-state transition were limited to O^{16} states with natural or undetermined parities. The calculations of these energetic limits, for a given combination of levels in O^{16} and C^{12}, were carried out in two steps. From machine calculations of the kinematics of the reactions $N^{14}(t,n)O^{16*}$ and $O^{16*} \to C^{12}+\alpha$, the limiting alpha energies at the angle of observation were determined from the range of possible angles and energies of the recoiling O^{16*} nucleus. The connected arrows then denote the limits of the alpha energies so obtained, corrected for appropriate energy losses in the target. The wide range of alpha energies from each transition resulted from the wide range of angles and energies of the O^{16*} from the first stage of the process.

Single arrows indicate the energetic end points for alpha particles from the reactions with which they are labeled.

Several definite structural features are evident in the alpha spectrum of Fig. 7. These features are attributed to the two-stage process $N^{14}(t,n)O^{16*}(\alpha)C^{12}$ on the basis of the relative independence of their positions of triton bombarding energy. In contrast to the case of the proton spectrum from $N^{14}(t,n)O^{16*}(p)N^{15}$, which was reported earlier,[1] it was not possible in the case of the alpha spectrum to obtain clearly defined groups corresponding to particular O^{16} levels. This difficulty was due primarily to the relatively large contribution of the continuum from $N^{14}(t,\alpha n)C^{12}$ which underlaid the alpha spectrum and tended to obscure broad groups superimposed on it.

The spectra at various triton energies exhibited two rather sharp discontinuities, labeled A and B, which were interpreted as the high-energy edges of groups from the two-stage process. They correspond fairly well with the calculated high-energy limits for the groups from the alpha decay from the levels in O^{16} at 13.10 MeV (1^-, $\Gamma=130$ keV) and 15.42 MeV (3^-, $\Gamma=96$ keV) to the C^{12} ground state. The low-energy edges of these groups could not be distinguished in the spectra. Three other, rather definite features of the spectra, labeled

C, D, and E, were evident. These groups were narrower than any of the predicted groups but they may have been particularly peaked portions of broader groups. An asymmetric distribution of this nature was observed in the proton groups from $N^{14}(t,n)O^{16*}(p)N^{15}$. The shape of the particle group from an O^{16} level would depend both on the angular distribution of the recoiling O^{16*} nuclei from the first stage of the reaction and on the angular distribution of the alphas or protons relative to the direction of motion of the O^{16*} nuclei in the second stage of the reaction. These three narrow features in the spectra could not be identified with particular O^{16} levels. Calculations were made for several alpha transitions to the 4.43-MeV state in C^{12} but the large number of transitions which could yield alphas in this energy region made any attempt to correlate spectral features with specific transitions fruitless.

The alpha yield from a given O^{16} level in the two-stage reaction $N^{14}(t,n)O^{16*}(\alpha)C^{12}$ depends both on the population of that level by the (t,n) reaction and on the probability of alpha decay of the level. Information on the alpha and proton partial widths of O^{16} levels in the region of excitation of interest here can be obtained from experiments in which O^{16} is formed as a compound nucleus. Such experiments include determinations of the excitation functions for the products of $N^{15}+p$ and for the scattering of alpha particles by C^{12}.

The experiments reported here in which O^{16*} was formed by $N^{14}(t,n)$ indicate that the O^{16} levels at 13.10, 14.94, 15.42, and 16.22 MeV were populated to an appreciable degree. Proton emission was observed from the levels at 14.94 and 16.22 MeV while alpha emission to the C^{12} ground state was observed from those at 13.10 and 15.42 MeV. Emission of alphas to the C^{12} ground state was forbidden by spin and parity conservation from the 1^+ level at 16.22 MeV in O^{16}.

Alpha-particle spectra were obtained for a range of triton energies from 1.8 to 2.6 MeV. The spectral features A–E exhibited the independence of position of

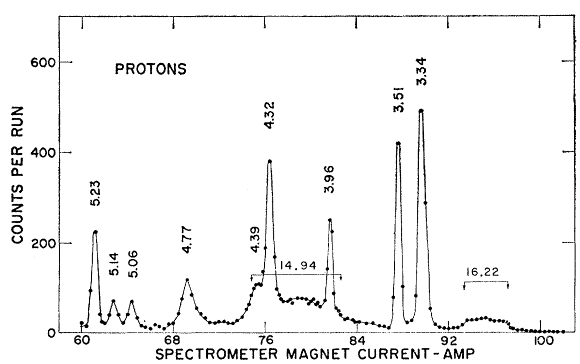

FIG. 8. Proton spectrum at 90° (lab) from the bombardment of nitrogen with 2.6-MeV tritons. [Compare with Fig. 1, reference 1(a)]. Groups corresponding to energy levels in N^{16} are labeled with excitation energies in MeV. The connected arrows indicate the calculated energy limits of protons from the two-stage process $N^{14}(t,n)O^{16*}(p)N^{15}$ (g.s.) proceeding through the 14.94- and 16.22-MeV states in O^{16}.

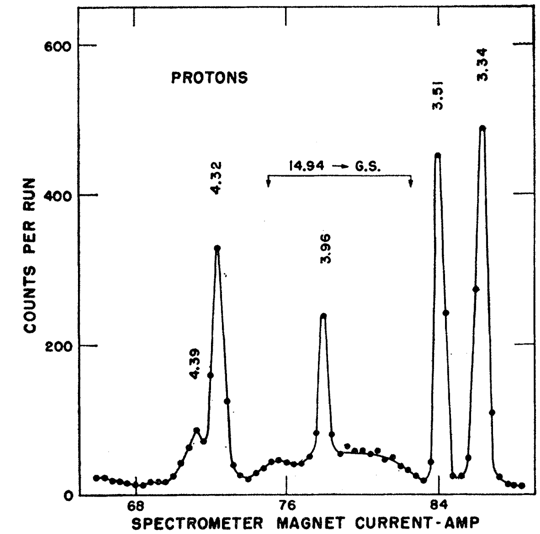

FIG. 9. Partial proton spectrum at 90° (lab) with 2.3-MeV tritons, to show the two-stage group $N^{14}(t,n)O^{16}(14.94)(p)N^{15}$ (g.s.) unobscured by N^{16} groups.

bombarding energy that is characteristic of the two-stage process, and the relative movement of C^{13} groups allowed these features to be observed as the C^{13} groups were moved over them. An alpha spectrum (Fig. 6) was also taken at 90° (lab) at a triton energy of 2.6 MeV. Particularly striking in several of the spectra at 30° and also discernible at 90° was the feature labeled C. It differed from other two-stage groups in that it was quite symmetric and closely resembled a rather broad C^{13} group. Other two-stage groups, such as E, were broader and flat topped, and therefore did not resemble groups corresponding to single C^{13} levels. A comparison of Figs. 2 and 5(c) demonstrates the relative shift in position between C and the 8.85-Mev C^{13} group when the triton energy was changed from 2.6 to 2.5 MeV. At lower triton energies the 8.85-MeV C^{13} group was superimposed on C.

TABLE II. Laboratory differential cross sections for various features of the proton and alpha spectra. Triton bombarding energy was 2.6 MeV. The estimated absolute standard deviations in the cross sections are ±25%.

Feature	Lab angle (deg)	Cross section (mb/sr)
Entire alpha continuum excluding C^{13} groups	30 90	30 18
Two-stage alpha group (B; 13.1-MeV O^{16} level)	30	1.5
Sum of C^{13} groups, except ground state group	30	15
Proton continuum above 60 A magnet current, excluding N^{16} groups and two-stage groups	30 90	4.4[a] 4.2
Low-energy two-stage proton group (14.94-MeV O^{16} level)	30 90	1.2[a] 1.2
High-energy two-stage proton group (16.22-MeV O^{16} level)	30 90	0.31[a] 0.27

[a] Reference 1.

No alpha groups were observed that could be attributed to the reaction $N^{14}(t,C^{12})He^5(\alpha)n$.

Table II gives a comparison between the cross sections for various features of both the proton and alpha spectra at 30 and 90° for 2.6-MeV tritons. In determining these cross sections it was assumed that no C^{13} alpha groups were produced with energies below those observed and that a rough extrapolation could be made for the continuum below this point. The alpha continuum cross section at 90° was about 60% of that at 30°.

Comparison can also be made between the proton cross sections at 90° reported in the present experiment and those at 30° reported previously.[1] The cross sections for the proton continuum and for the low-energy (14.94-MeV O^{16} level) and high-energy (16.22-MeV O^{16} level) two-stage groups were nearly equal at the two angles. Good agreement was again obtained between the observed and the calculated energy limits of the two-stage groups of protons from $N^{14}(t,n)O^{16*}(p)N^{15}$. Figure 9, obtained at $E_t=2.3$ MeV, shows the low-energy group with the interfering N^{16} groups shifted downward.

IV. SUMMARY

Information has been obtained concerning the positions of nuclear energy levels of C^{13} by observation of alpha-particle groups from $N^{14}(t,\alpha)C^{13}$. In addition to a continuous energy distribution of alphas from the three-body breakup reaction $N^{14}(t,n\alpha)C^{12}$, certain features of the spectra were observed which could be attributed to the two-stage reaction $N^{14}(t,n)O^{16*}(\alpha)C^{12}$. The presence of particle groups associated with two-stage reactions of this nature may present experimental difficulties in certain investigations of particle spectra because of possible confusion with particle groups from the reaction of primary interest.