Nuclear Energy Levels in C^{13}, N^{13}, N^{14}, N^{15}, O^{15}, and F^{18} from He^3 Induced Reactions*

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The Rice Institute 5.5-Mev Van de Graaff accelerator and a magnetic spectrograph have been used to study reaction products produced by He^3 bombardment of B^{11}, C^{12}, C^{13}, N^{14}, and O^{16}. Q values of 9.5, 9.3, 6.31, 5.68, 5.63, 5.49, 4.31, 3.67, and 3.29 Mev were observed for the $B^{11}(He^3,p)C^{13}$ reaction, corresponding to excitations of from 3.7 to 9.90 Mev in C^{13}. The energy levels at 7.69 and 8.87 Mev in C^{13}, for which the Q values were 5.49 and 4.31 Mev, were determined to have widths of approximately 75 and 175 kev, respectively. For the $C^{13}(He^3,p)N^{15}$ reaction the observed Q values were 5.38, 4.33, 3.50, 3.36, 3.09, 2.35, 2.09, 1.61 and 1.50 Mev. The $O^{16}(He^3,p)F^{18}$ reaction revealed the existence of twelve states below 3.9 Mev of excitation in F^{18}. These states occur at 0.943, 1.047, 1.089, 1.128, 1.708, 2.102, 2.521, 3.058, 3.130, 3.355, 3.724, and 3.843 Mev of excitation. The ground-state Q values of the $O^{16}(He^3,\alpha)O^{15}$ and $N^{14}(He^3,d)O^{15}$ reactions were determined to be 4.91 and 1.80 Mev, respectively, and the first excited state of O^{15} was observed at 5.17 Mev by means of the $O^{16}(He^3,p)O^{15}$ reaction.

INTRODUCTION

GAS containing 90 to 100% He^3 has recently become available in quantities which allows He^3 to be used as the incident particle for extended bombardments of various target nuclei.[1] The low binding energy of this nucleus results in high excitations in the compound nuclear system, even when used with the moderate bombarding energies produced by an electrostatic accelerator. Since He^3 has an isotropic spin of $\frac{1}{2}$, its use permits the observation of some $T=1$ and $T=\frac{3}{2}$ levels which are not excited strongly in reactions involving deuterons and alpha particles.

No extensive investigations had been performed by studying the reaction products produced by He^3 bombardment. It was therefore decided to examine several of the light nuclei to determine if any previously unobserved energy levels could be detected. Since carbon and oxygen appear, at least in small quantities, as contaminants on most targets, they were chosen for early study.

EXPERIMENTAL DETAILS

A. General

A 180° magnetic spectrometer was used to study reaction products produced by bombardment of B^{11}, C^{12}, C^{13}, N^{14}, and O^{16} with He^3 ions from the Rice Institute 5.5-Mev Van de Graaff accelerator. Reaction products emitted at 180° to the incident beam were deflected through a semicircular path of about 35-cm radius. The spectrometer and the formulas necessary for the determination of Q values have been described previously.[2]

Ilford $E1$ photographic emulsions were used to detect the particles emitted during bombardment of the targets with approximately 500 microcoulombs of He^{3+} ions. It was possible to identify the type of particle by the length and density of the track produced in the emulsion when exposed at a given magnetic field. The reaction producing a given group of protons, deuterons, or alpha particles was determined from the shift in the energy of the emitted particles as a function of the energy of the incident He^3 ions. In some cases the target thickness furnished additional means of identifying the nucleus responsible for a given group of particles.

The bombarding energies used in the various experiments were calculated from the energies of He^3 ions scattered elastically from heavy nuclei, or from the energy of particles produced in reactions having known Q values. The two reactions most frequently used for this purpose were the $C^{12}(He^3,p)N^{14}$ and $O^{16}(He^3,p)F^{18}$ reactions, with the residual nuclei left in the ground state.

B. Targets

The ideal target for observation of narrow energy levels would be of a thickness such that the energy loss of the incident particles in passing through the target, plus the energy loss of the emitted particle in the target, would cause a shift in the diameter of the emitted particles' path approximately equal to the width of the incident beam. Since both the energy and type of particle effect the energy loss while traversing the target, it is impossible to fabricate a target which is of ideal thickness for observation of more than one type of emitted particle at one energy. The targets used were prepared to be as near as possible to optimum thickness for the highest energy protons observed. They were thus somewhat greater than optimum thickness for all other observations.

The B^{11} targets were prepared by evaporating electrolytic, natural boron onto thin carbon and nickel foils. Targets on nickel backings were utilized to examine

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[1] He^3 gas was purchased from Oak Ridge National Laboratory.
[2] Gossett, Phillips, and Eisinger, Phys. Rev. 98, 724 (1955).

regions of the proton spectrum which were observed by proton groups produced by reactions in the carbon backings. The evaporated boron layers on the carbon and nickel backings were approximately 5 and 2 kev thick, respectively, to the incident He^3 ions.

Carbon foils used for target backings and for C^{12} and C^{13} targets were prepared by cracking methyl iodide so that the carbon was deposited on a hot tantalum sheet. When cool, the carbon and tantalum separated because of the difference in coefficients of thermal expansion. The foils used were approximately 0.25 mg/cm². Methyl iodide enriched to 65% in C^{13} was used in preparing the foils employed for study of the $C^{13}(He^3,p)N^{15}$ and $C^{13}(He^3,d)N^{14}$ reactions.

A N^{14} target was prepared by heating a thin titanium foil to a bright cherry red in one-half atmosphere of NH_3. Titanium foils were made by evaporating a layer of about 0.25 mg/cm² of titanium metal onto a microscope slide which had been coated by dipping it into a solution of ordinary table sugar and water, to which had been added a few drops of commercial detergent. The foil was then removed by emersing the slide in water. The target prepared in this manner had a TiN layer on each side and oxide throughout the foil.

Two types of oxygen targets were employed during the course of the experiments to be discussed here. The first type was the foil described in the previous paragraph. The second type consisted of a thin foil of SiO. This foil was produced by evaporating SiO onto a collodion film. Under bombardment by the He^3 beam the collodion evaporated, leaving only the SiO foil as the target. These foils were approximately 5 kev thick to the incident He^3 beam.

EXPERIMENTAL RESULTS AND DISCUSSION

A summary of the energy level determinations to be discussed in this section is presented in Table I. The code numbers in column 1 refer to particular particle groups in the succeeding spectra. In Figs. 1 and 2 certain groups appear which are not discussed in the text. Specifically, these are the ones which correspond to residual nuclei of masses less than 13. A discussion of the corresponding reactions will be included in a later paper.

Approximate values for the energies of observed particles corresponding to the peaks in the various spectra can be obtained from the relationship:

$$E=A(B\rho)^2\times10^{-5};$$

where A has the value 4.789 for protons, 2.396 for deuterons, 6.399 for He^3 ions, and 4.822 for alpha particles. $B\rho$ is given as the abcissa of each spectrum. The bombarding energy, E_1, is given on each figure.

A. Energy Levels in C^{13} and N^{13}

The energy level structure of C^{13} was studied by means of the $B^{11}(He^3,p)C^{13}$ reaction for excitations in the residual nucleus between 3.6 and 10 Mev. In Fig. 1 a proton spectrum is shown which corresponds to excitations between 3.6 and 9.9 Mev in C^{13}. The section of the spectrum on the right was observed at an incident He^3 energy of approximately 3 Mev. The section on the left, observed at an incident energy of 4.9 Mev, corresponds to excitations of from 4.6 to 9.9 Mev. It was necessary to study the lower region of excitation in C^{13} at the reduced bombarding energy, because, at the higher energy, protons leaving the nucleus excited to between 3.6 and 4.6 Mev were too energetic to be studied with the spectrometer.

Proton groups 1 through 9 have been assigned to

TABLE I. Compilation of experimental results discussed in the text. Estimated errors in Q values and energies of excitation are given in kev immediately following these energies in Mev. Level widths are given only for the cases in which the use of thin targets permitted a significant determination.

Group and number of determinations	Reaction	Q (Mev)	Energy of excitation (Mev)	Level width (kev)
1 (1)	$B^{11}(He^3,p)C^{13}$	~9.5	~3.7	<5
2 (1)		~9.3	~3.9	<5
3 (2)		6.313 (7)	6.871 (12)	<10
4 (2)		5.684 (7)	7.500 (12)	<5
5 (2)		5.630 (7)	7.554 (12)	<5
6 (2)		5.490 (10)	7.694 (14)	75±15
7 (2)		4.315 (35)	8.869 (36)	175±50
8 (2)		3.675 (8)	9.509 (12)	<10
9 (2)		3.288 (8)	9.896 (12)	<10
10 (2)	$N^{14}(He^3,\alpha)N^{13}$	10.015 (10)	0.000 (−)	···
11 (1)		7.655 (15)	2.361 (18)	···
12 (1)		~6.46	~3.55	···
13 (1)	$C^{13}(He^3,d)N^{14}$	2.050 (15)	0.000 (−)	···
14 (1)		−0.265 (15)	2.315 (22)	···
15 (4)	$C^{12}(He^3,p)N^{14}$	4.764 (7)	0.000 (−)	···
16 (1)		2.451 (15)	2.313 (17)	···
17 (2)		0.818 (15)	3.946 (17)	···
41 (2)		−0.124 (16)	4.888 (18)	···
42 (2)		−0.314 (16)	5.078 (18)	···
43 (2)		−1.048 (16)	5.812 (18)	···
18 (3)	$C^{13}(He^3,p)N^{15}$	5.385 (7)	5.283 (12)	···
19 (3)		4.335 (7)	6.333 (12)	···
20 (2)		3.499 (7)	7.169 (12)	···
21 (2)		3.358 (7)	7.310 (12)	···
22 (2)		3.095 (8)	7.577 (13)	···
23 (2)		2.350 (7)	7.318 (12)	···
24 (1)		2.087 (10)	8.581 (14)	···
25 (1)		1.607 (10)	9.061 (14)	···
26 (1)		1.504 (10)	9.164 (14)	···
27 (4)	$O^{16}(He^3,\alpha)O^{15}$	4.907 (7)	0.000 (−)	···
44 (3)		−0.260 (12)	5.167 (15)	···
28 (2)	$N^{14}(He^3,d)O^{15}$	1.803 (10)	0.000 (−)	···
29 (2)	$O^{16}(He^3,p)F^{18}$	2.033 (5)	0.000 (−)	<5
30 (7)		1.090 (5)	0.943 (7)	<5
31 (8)		0.986 (5)	1.047 (7)	<5
··· (3)		0.944 (5)	1.089 (7)	<5
32 (7)		0.905 (5)	1.128 (7)	<5
33 (3)		0.325 (5)	1.708 (7)	<5
34 (4)		−0.069 (5)	2.102 (7)	<5
35 (2)		−0.488 (8)	2.521 (10)	<5
36 (2)		−1.025 (8)	3.058 (10)	<5
37 (2)		−1.097 (8)	3.130 (10)	<5
38 (2)		−1.322 (8)	3.355 (10)	<5
39 (2)		−1.691 (8)	3.724 (10)	<5
40 (2)		−1.810 (8)	3.843 (10)	<5

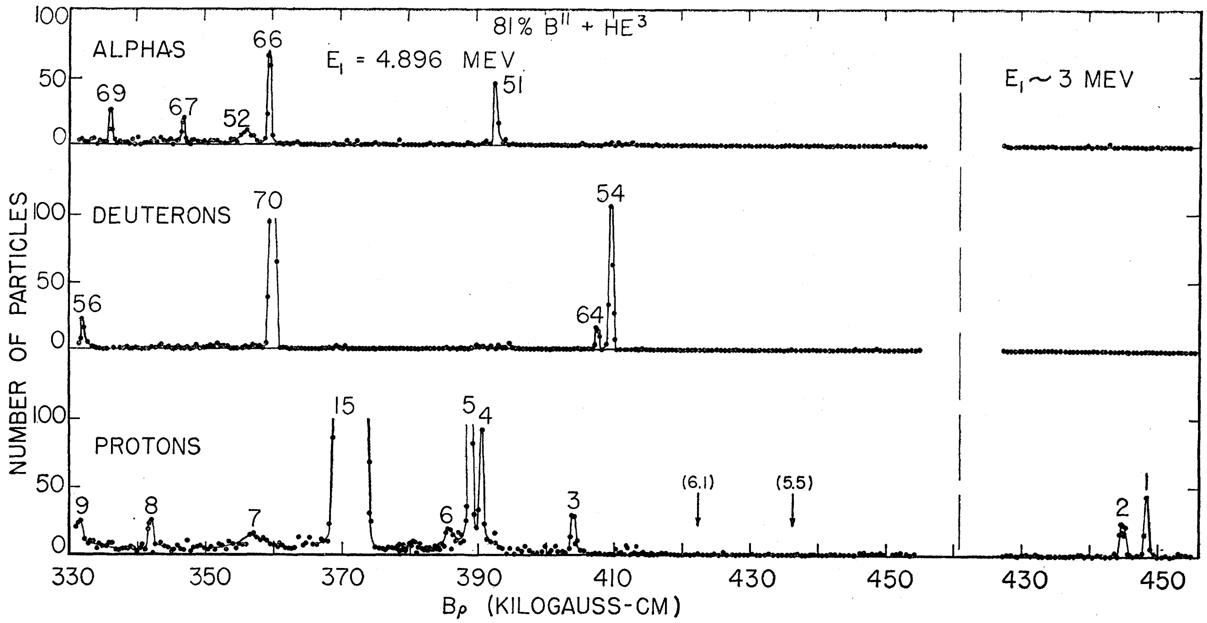

FIG. 1. Particle spectra from target of natural boron evaporated onto a carbon foil. Proton groups 1 through 9 correspond to states in C^{13} between 3.6 and 9.9 Mev. Bombarding energies, E_1, are indicated by the values of E_1 shown on the figure.

energy levels in C^{13}. Groups 1, 2, 3, 4, 5, 7, and 9 showed energy spreads which indicated that the corresponding states at 3.68, 3.86, 6.87, 7.50, 7.55, 9.51, and 9.90 Mev, respectively, had widths of less than 10 kev.

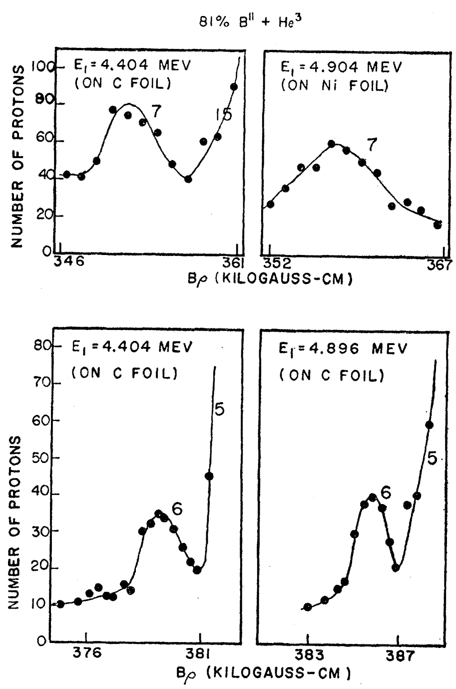

FIG. 2. Partial spectra of protons produced by natural boron targets. The target backing material is indicated on each section of the figure. Proton groups 6 and 7 correspond to states at 7.69 and 8.87 Mev, respectively.

The proton groups corresponding to broad states at 7.69 and 8.87 Mev are plotted on an expanded scale in Fig. 2. Group number 7, shown in the upper part of the figure, also has more particles plotted for a given increment of $B\rho$. The region of the spectrum where this proton group occurs shows a background due to the protons from the $C^{12}(He^3,p)N^{14}$ ground-state reaction, and from $C^{13}(He^3,p)N^{15}$ reaction leaving N^{15} excited to 6.33 Mev. The background is greatly reduced in the spectrum of the region of the 8.87-Mev state which was obtained by using boron evaporated onto a thin nickel foil. This partial spectrum is shown in the upper right section of Fig. 2. The states in C^{13} at 7.69 and 8.87 Mev have widths of approximately 75 and 175 kev, respectively.

Magnetic field limitations prevented an independent determination of the Q value of the $B^{11}(He^3,p)C^{13}$ reaction with C^{13} left in its ground state. The ground-state Q value used in the calculation of energies of excitation shown in Table I was calculated from atomic masses given by Wapstra.[3] The value of the ground-state Q was taken to be 13.184 ± 0.009 Mev.

Groups of alpha particles were observed from the $N^{14}(He^3,\alpha)N^{13}$ reaction with N^{13} left in its ground state. In addition, lower energy alpha-particle groups were observed which probably resulted from this reaction with N^{13} being left in the first three excited states, with the second and third giving a single broad group of particles. These alpha particles are plotted as groups 10, 11, and 12 in Fig. 3. Group 12 would indicate a broad state in N^{13} with an excitation of approximately

[3] A. H. Wapstra, Physica **21**, 367 (1955).

3.55 Mev. When the uncertainty in the target thickness is considered, this energy is compatible with assignment of the particles to the known states at 3.51 and 3.56 Mev.

The region of excitation of N^{13} between 4.7 and 5.8 Mev was investigated by the elastic scattering of protons from C^{12}. The target for the experiment was prepared by deposition of carbon from an arc onto a 4-microinch thick nickel foil. The target was about 2 kev thick to the incident protons, and data points were taken at 4-kev intervals using a scintillation counter at the position usually occupied by the photographic plates. No indication of narrow states was observed in the region of excitation studied, but it is possible that states with a laboratory width of as much as 2 or 3 kilovolts could have escaped detection.

A recent investigation[4] has given evidence, from the $B^{11}(He^3,p)C^{13}$ reaction, for states at 5.51 ± 0.005 and 6.10 ± 0.05 Mev of excitation in C^{13}. These authors reported the observation of the two proton groups of 5 to 10% of the intensity of the group which leaves C^{13} in its ground state. The positions where groups of protons corresponding to these states would occur are indicated by arrows in Fig. 1. These states, and their mirror states, are expected to be narrow since they have not been observed by neutron or proton scattering from C^{12}. For states less than 50 kev wide, the intensity of the proton groups, at a bombarding energy of 4.9 Mev, must be less than 10% of the intensity of the group leaving C^{13} excited in the 6.87-Mev state, or they would have been observed in the present experiment. All states observed by means of the present experiment, at incident energies of 4.4 and 4.9 Mev, showed intensities not less than one half that of the 6.87-Mev state.

Proton groups 4 and 5, shown in Fig. 1, are due to narrow levels at 7.50 and 7.55 Mev of excitation. These levels have been reported at 7.47 and 7.53 Mev, from the $C^{12}(d,p)C^{13}$ reaction.[5] A proton group corresponding to a state at 7.55 Mev, and probably due to the two levels observed here, has been observed from the $B^{11}(He^3,p)C^{13}$ reaction.[4] Two more levels with widths of less than 10 kev were observed at excitations of 9.51 and 9.90 Mev. These states have been previously reported from the present reaction, as well as from the $N^{15}(d,\alpha)C^{13}$ and $C^{12}(d,p)C^{13}$ reactions.[4–6]

The broad (75 ± 15 kev) state indicated by proton group 6 in Fig. 1 and Fig. 2 has been observed previously by both charged particle and neutron scattering experiments.[5,7] The neutron scattering experiment indicated that this is a $D_{\frac{3}{2}}$ state. The other broad (175 ± 50 kev) state observed by the present experiment

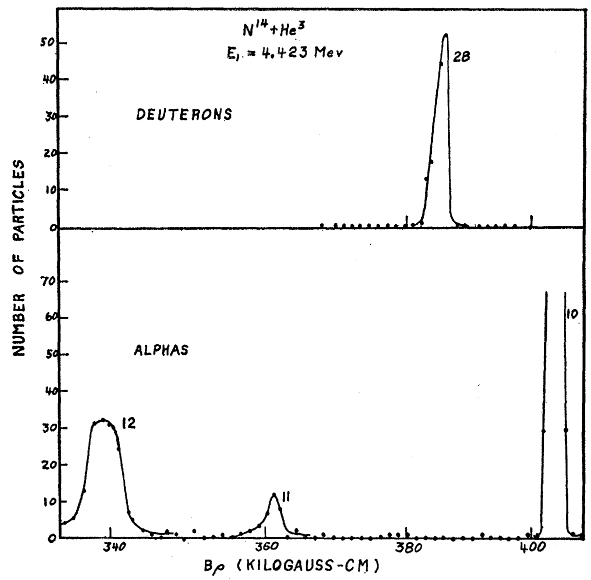

FIG. 3. Spectra of alpha particles and deuterons from bombardment of TiN with He^3 ions. Group 12 includes the second and third excited states of N^{13}.

has been reported previously from studies of the $B^{11}(He^3,p)C^{13}$ reaction,[4] and also probably corresponds to the level reported at 8.80 Mev from the $N^{15}(d,\alpha)C^{13}$ reaction.[6] Another broad ($\sim$1 Mev) state has been reported from the $C^{12}(d,p)C^{13}$ reaction[5] and from elastic scattering,[7,8] but was not observed in the present experiment. However, if this broad state gave approximately the same yield of protons as the others observed it would have been masked, in the present experiment, by protons from sources other than the B^{11} target.

Figure 4 shows energy level diagrams of the mass 13 nuclei. The diagram on the left gives the experimentally known levels in C^{13}, with the region of excitation examined by the present experiment indicated by the arrow at the right. The levels denoted by short lines at

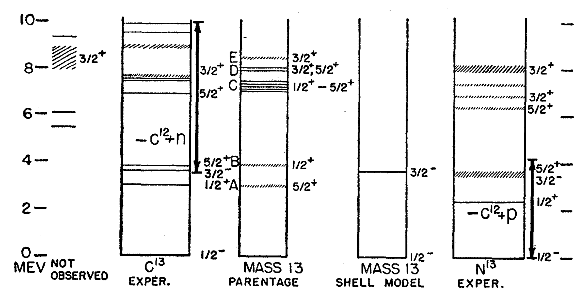

FIG. 4. Level diagram of the mass 13 nuclei. Arrows at the right of the experimental diagrams indicate the regions of excitation examined in the present experiment. The letters at the left of the nuclear parentage model diagram indicate the following origins of states: A, C^{12}(gnd)$+1d$ nucleon; B, C^{12}(gnd)$+2s_{\frac{1}{2}}$ nucleon; C, C^{12*}(4.43 Mev)$+1d$ nucleon; D, C^{12*}(4.43 Mev)$+2s_{\frac{1}{2}}$ nucleon; and E, C^{12}(gnd)$+1d_{\frac{3}{2}}$ nucleon.

[4] Galonsky, Moak, Traughber, and Jones, Phys. Rev. **110**, 1360 (1958).
[5] McGruer, Warburton, and Bender, Phys. Rev. **100**, 235 (1955).
[6] E. K. Warburton and J. N. McGruer, Phys. Rev. **105**, 639 (1957).
[7] R. Budde and P. Huber, Helv. Phys. Acta **28**, 49 (1955).
[8] Freir, Tulk, Lampi, and Williams, Phys. Rev. **78**, 508 (1950).

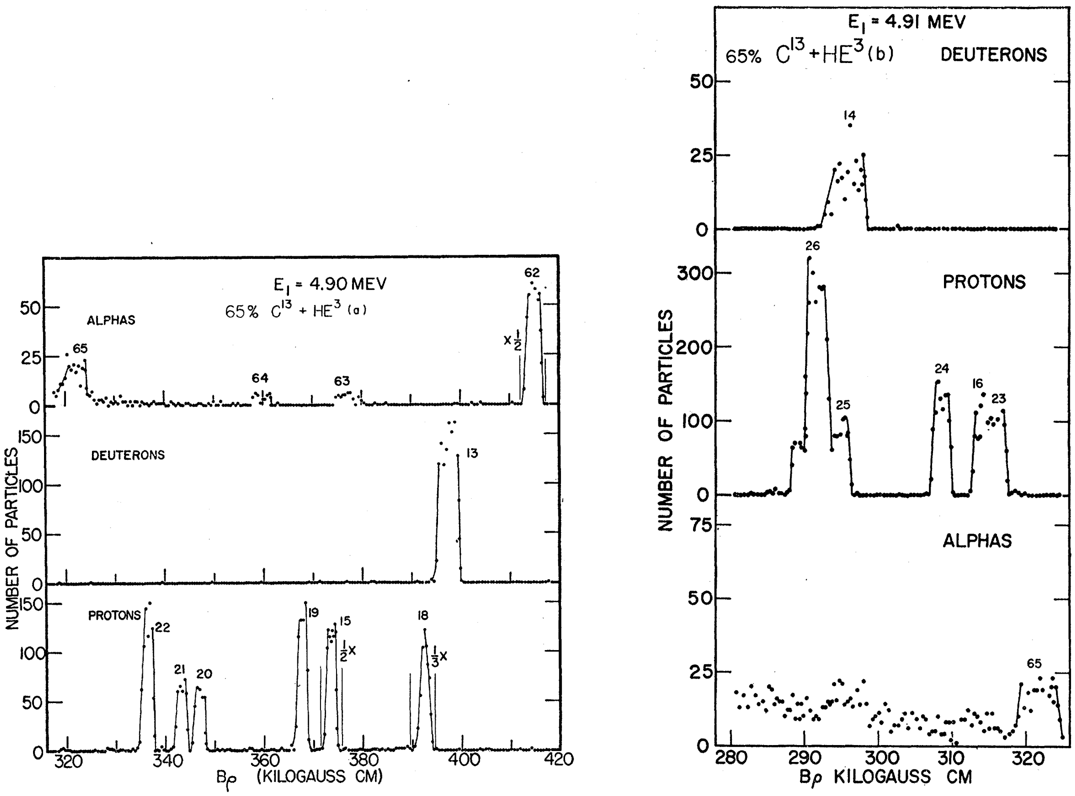

FIG. 5. Particle spectra from carbon foil target, prepared from methyl iodide enriched to 65% in C^{13}. Proton groups 18 through 26 correspond to states between 4.5 and 9.5 Mev in N^{15}. Groups 16 and 17 are from the first and second excited states in N^{14}.

the left of the main plot are those which have been reported, but were not observed in the present experiment. Spins and parties are shown for the levels for which determinations are available. On the right side of the figure is a similar plot for N^{13}.

A simple model of the mass 13 nuclei may be constructed by assuming that the energy levels are due to the addition of a single nucleon to the C^{12} core, or the existence of a nucleon hole in a N^{14} core. In this nuclear parentage model, the core may be either in its ground state or an excited state. The added nucleon, or hole, is described by the appropriate shell model quantum numbers. The center diagrams in Fig. 4 show the positive parity states which Lane and Thomas[9] predicted by assuming *s*- and *d*-wave nucleons about a C^{12} core, and an *s*-wave hole in a N^{14} core. The negative parity states shown are taken from calculations by Kurath.[10]

Two of the states in N^{13} have been shown to have the character predicted by this model.[11] These are the $\frac{3}{2}+$ and $\frac{5}{2}+$ levels at 6.90 and 6.38 Mev in N^{13} and produced by $2s_{\frac{1}{2}}$ protons about the C^{12} core excited to the 4.43-Mev state. A comparable assignment for the C^{13} nucleus would be to associate the $\frac{3}{2}+$ level with the state at 7.69 Mev, and the $\frac{5}{2}+$ level with the 6.78-Mev state. This assignment leaves the five states due to a $1d_{\frac{5}{2}}$ nucleon about a C^{12} core excited to 4.43 Mev still to be accounted for.

B. The N^{14} Nucleus

The ground state and five excited states of N^{14} have been observed by means of the $C^{12}(He^3,p)N^{14}$ reaction. The ground-state Q value for the $C^{13}(He^3,d)N^{14}$ reaction has also been determined. The $C^{12}(He^3,p)N^{14}$ ground-state group is shown in Fig. 5 as peak number 15, and the groups corresponding to the excited states appear as peaks numbered 16, 17, 41, 42, and 43 in Fig. 7. These latter groups were produced by the carbon contaminant which was deposited on the SiO foil during bombardment. The Q values obtained agree fairly well with those expected from the masses involved and the results of previous experiments[12] giving the excitations of levels in N^{14}. Levels at about 5.69 and

[9] A. M. Lane and R. G. Thomas (private communication) [Revs. Modern Phys. (to be published)].
[10] D. Kurath, Phys. Rev. **101**, 216 (1956).
[11] Reich, Phillips, and Russell, Phys. Rev. **104**, 143 (1956).
[12] F. Ajzenberg and T. Lauritsen, Revs. Modern Phys. **27**, 77 (1955).

5.98 Mev were not observed. Further investigation of this nucleus is planned, and a thin carbon foil will be used for a target.

C. Excited States in N^{15}

Proton groups 18 through 26 in Fig. 5, represent states in N^{15} between 4.5 and 9.5 Mev of excitation. The energy loss in the target material caused a spread in the energy of the outgoing particles to an extent which prevented separate identification of proton groups corresponding to the 5.283-Mev state and the state reported at about 30 kev higher energy.[13] Groups 25 and 26, although not separated, were of sufficiently different energies to permit accurate determination of the Q values for states at 9.06 and 9.16 Mev in N^{15}. The lowest six states were observed at two different bombarding energies, and therefore may be definitely assigned to the $C^{13}(He^3,p)N^{15}$ reaction. Proton groups 24, 25, and 26 were observed at only one bombarding energy. These groups are of the proper width to be associated with either the $C^{12}(He^3,p)N^{14}$ or the $C^{13}(He^3,p)N^{15}$ reaction. Since assumption of the former reaction would indicate the existence of energy levels in the thoroughly investigated region between the 2.31- and 3.95-Mev states it is possible to assign these groups to the $C^{13}(He^3,p)N^{15}$ reaction. The energies of excitation shown in Table I were obtained using a ground-state Q value of 10.668 ± 0.010 Mev, which was calculated from the masses.[3] Energies obtained in this manner are in excellent agreement with the results of the $N^{14}(d,p)N^{15}$ reaction reported by Malm and Buechner.[13] Accurate widths could not be determined from the results of the present experiment, but a maximum of about 25 kev is applicable for all the observed states.

An energy level diagram of the region of excitation studied is shown in Fig. 6. The experimental spins and parities shown are those listed by Ajzenberg and Lauritsen,[12] except for the 7.58-Mev level.[6] The diagram on the left side of the figure gives the positive parity states predicted by the shell-model calculations of Halbert and French.[14] Lines drawn between the left and center diagrams indicate the assignments suggested when the calculations were made. The diagram on the right of Fig. 6 shows states which can be predicted by a very simple nuclear parentage model. To obtain this level structure, it was assumed that the amount of splitting of levels of different J depended on the values of j and n, the shell model quantum numbers of the individual nucleons added to a core. The multiplets of higher j are split more, as are the multiplets of higher n. The ground state is assigned to a $1p_{\frac{1}{2}}$ proton hole in the ground state of the O^{16} nucleus, and the negative parity state at 6.33 Mev to a $1p_{\frac{1}{2}}$ hole in O^{16} excited to the 6.06 Mev (0^+) state. It appears that the proper

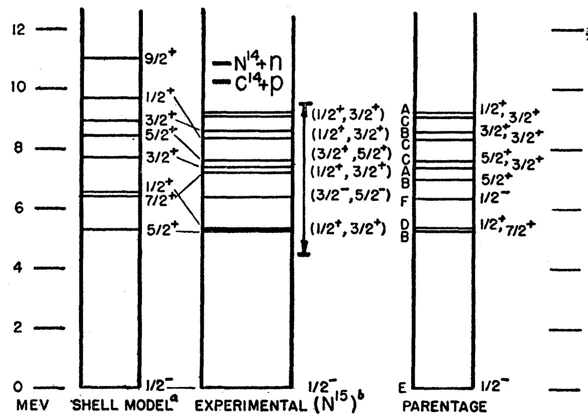

FIG. 6. Level diagrams of N^{15}. The code numbers for the nuclear parentage states indicate the following structure: A, $N^{14}+2s_{\frac{1}{2}}$ neutron; B, $N^{14}+1d_{\frac{5}{2}}$ neutron; C, $N^{14}+1d_{\frac{3}{2}}$ neutron; D, O^{16*}(6.06 Mev)$-1s_{\frac{1}{2}}$ proton; E, $O^{16}-1p_{\frac{1}{2}}$ proton; F, O^{16*} (6.00 Mev)$-1p_{\frac{1}{2}}$ proton. The superscript a refers to reference 14. The superscript b refers to the compilation in reference 12 and to the present determination.

number of states of proper parity, in the region below 10 Mev, can be accounted for by a nuclear parentage model. However, more detailed experimental and theoretical work is required before the worth of the concept can be established.

D. The O^{15} Nucleus

Two particle groups have been observed from reactions which left O^{15} in its ground state. These were alpha particles from the $O^{16}(He^3,\alpha)O^{15}$ reaction, which gave peak number 27 in Fig. 7(a), and deuterons from the $N^{14}(He^3,d)O^{15}$, which gave peak number 28 in Fig. 3. Both of these reactions had Q values different from those expected from the published mass values,[3] but agree with recent $N^{15}(p,n)O^{15}$ and beta decay experiments.[15,16] If each of the recent independent determinations is given the same weight, the results show that the published mass value[3] for O^{15} is too low by $(60\pm5)\times10^{-6}$ amu.

An investigation of the region of the first excited state of O^{15} gave a Q value of -0.260 Mev for the $O^{16}(He^3,\alpha)O^{15}$ reaction, which corresponds to an excitation of 5.167 Mev. The partial spectrum of this region which had the best statistics failed to show a doublet structure for the state. Whether this was due to greatly different alpha particle yields from two states, the overlapping of two states, or the occurrance of only one state instead of the two expected by comparison with N^{15}, was not determined.

E. Energy Levels in F^{18}

The energy level structure of F^{18} has been studied for excitations from 0 to 3.9 Mev by means of the

[13] R. Malm and W. W. Buechner, Phys. Rev. **80**, 771 (1950).
[14] E. C. Halbert and J. B. French, Phys. Rev. **105**, 1563 (1957).
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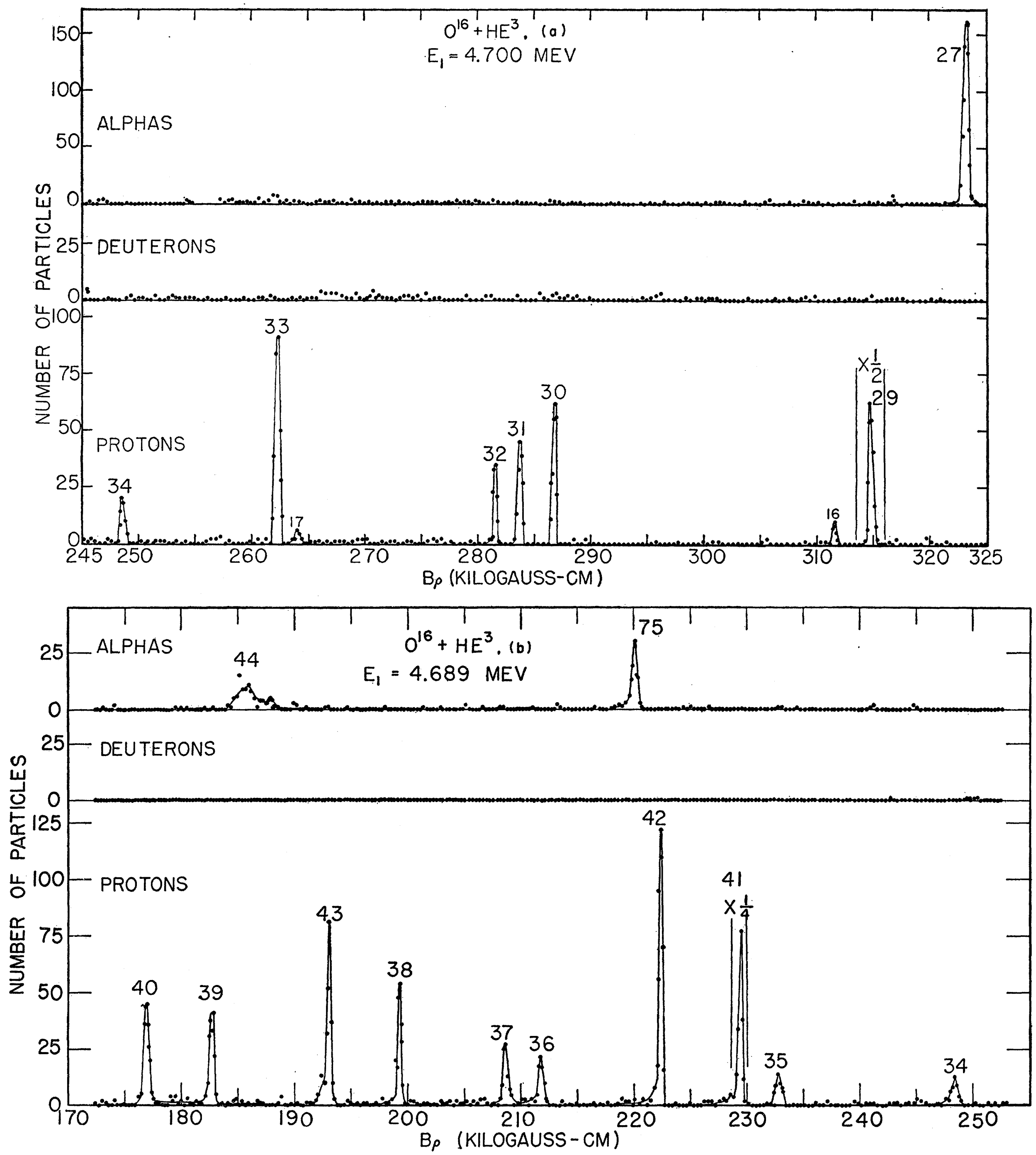

FIG. 7. Particle spectra from SiO foil target. Proton groups 29 through 40 represent states from 0 to 3.9 Mev of excitation in F^{18}. Groups 16, 17, 41, 42, and 43 correspond to states in N^{14}, and 27 and 44 to the ground and first excited state of O^{15}.

$O^{16}(He^3,p)F^{18}$ reaction. Proton groups 29 through 40, in Fig. 7, correspond to the observed states. In addition, the spectrum near 1 Mev of excitation has been studied in detail and is shown in Fig. 8 where four excited states of F^{18} are observed. The ground-state Q value of 2.033 Mev was determined using the bombarding energy obtained by elastic scattering of He^3 from the various Ti isotopes and from Cu^{65}. The incident energy for the spectrum shown in Fig. 7(a) was then determined using this ground-state Q value. The bombarding energy for the spectra giving the region of excitation near 1 Mev (Fig. 8) and from 2.0 to 3.9 Mev (Fig. 7) was calculated from the Q value previously determined for the reaction to the 2.102-Mev state.

Previous investigators have reported evidence for energy levels at 0.94, 1.05, 1.74, 2.09, 2.54, 3.07, and 3.35 Mev in the region of excitation examined in the present experiment.[17–22] States unobserved in these studies have been found at 1.09, 1.12, 3.13, 3.72, and 3.84 Mev. Peak number 38 in Fig. 7, which has been assigned to the previously reported state at 3.35 Mev in F^{18}, appears at a $B\rho$ value which corresponds to that expected for a proton group from the $C^{12}(He^3,p)N^{14}$ reaction leaving N^{14} excited to approximately 5.7 Mev. Since considerable carbon contaminant built up on the target, as indicated by groups 41, 42, and 43, it was expected that this group should also appear. However, the shift of proton energy with bombarding energy indicated that the group was primarily due to the $O^{16}(He^3,p)F^{18}$ reaction.

For excitations below 2 Mev, the shell-model calculations[23] for F^{19} have been found to give excellent agreement with the observed structure. No such agreement has been demonstrated yet for the low-lying levels in F^{18}.

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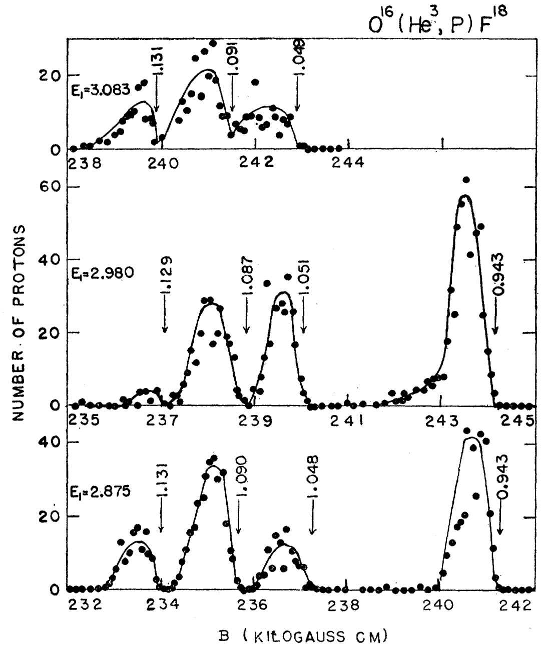

FIG. 8. Partial spectra at three different bombarding energies for the reaction $O^{16}(He^3,p)F^{18}$ for the region of excitation near 1 Mev.

It should be noted that the variations in intensity with bombarding energy for the states near 1-Mev excitation show that there is pronounced resonance structure in the excitation functions for these proton groups. This effect renders the identification of the F^{18} levels rather difficult.