Study of Some Levels of C^{12} Using the $B^{10}(He^3,p)C^{12*}$ Reactions

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Studies of the $B^{10}(He^3,p)C^{12*}$ reaction using 2-Mev He^3 ions showed proton groups corresponding to levels in C^{12} at 0, 4.43, 7.65, 9.60, 10.76, 11.82, 12.78, 13.37, 14.03, 15.10, 16.10, and 16.64 Mev±0.10 Mev. The ratio $\Gamma_\gamma:\Gamma$ was measured to be 0.75(±0.20) for the 15.1-Mev state and 0.02(±0.01) for the 12.78-Mev state. No other alpha unstable level had a measurable $\Gamma_\gamma:\Gamma$; for the 7.65-Mev state a limit 0.01 is set on this ratio. The gamma-ray de-excitation of the 15.1-Mev state is both to the ground state (97%) and to the 4.43-Mev state (3.1±0.6%). Only a ground state transition was observed from the 12.78-Mev level. These measurements support assignments, J, π, T of 1, +, 1 to the 15.1 level and 1, +, 0 to the 12.78-Mev state. The known properties of C^{12} are in fair agreement with the intermediate coupling shell-model calculations of Kurath. The reactions $C^{13}(He^3,\alpha\gamma)C^{12}$(15.1 Mev) and $B^{10}(He^3,d)C^{11}$ to the ground and first excited state of C^{11} were observed.

1. INTRODUCTION

THE high Q-value of the $B^{10}(He^3,p)C^{12}$ reaction permits the use of low-energy He^3 ions to produce C^{12} in high excitations. Using 900-kev bombarding energy Bigham, Allen, and Almqvist[1] observed levels in C^{12} at 4.43, 7.77, 9.61, 10.75, 11.83, 12.76, 13.31, 13.97, 15.10, 16.04, and 16.57 Mev (±0.10). These have also been observed by Moak *et al.*[2] at Oak Ridge using 1.25-Mev ions; in addition these authors reported a level at 15.62 Mev. This level was not seen in the present work using 2.0-Mev He^3 ions. The levels of C^{12} have also been studied in a number of other reactions listed in the review article by Ajzenberg and Lauritsen.[3]

In the present studies of the reactions produced by He^3 bombardment of B^{10}, 90° differential cross sections at 2 Mev were measured for the production of the various proton and deuteron groups as well as 90° excitation functions for all neutrons, 15.1-Mev gamma radiation and protons to the 4.43-Mev state over the range 1.1–2.6 Mev. Detailed studies using coincidence techniques have been made of the properties of the states which de-excite by gamma-ray emission. These studies show that the $(He^3,d\gamma)$ reaction via the first excited state of C^{11} occurs as well as $(He^3,p\gamma)$ reactions via states in C^{12} at 15.1 Mev, 12.78 Mev, and 4.43 Mev. No other state in C^{12} below 16 Mev excitation was found with a gamma-ray width equal to or greater than 1% of its total width.

Particular interest centers on the level at 15.1 Mev first observed by Johnson,[4] which is almost certainly the $T_z=0$ member of the isobaric triplet comprising it and the ground states of N^{12} and B^{12}. This level has sufficient excitation to break up into three alpha-particles, either directly or via states in Be^8 with an energy release of 7.8 Mev. However alpha-particle breakup is forbidden if isobaric spin is to be conserved and the effectiveness of the isobaric spin selection rule can be measured by comparing the widths for de-excitation by gamma radiation and alpha-particle decay.

The first evidence that this state has a measurable gamma radiation width was the observation by Cohen *et al.*[5] of a 15.1-Mev gamma ray produced by the bombardment of carbon by protons ranging in energy from 30 to 340 Mev as well as in a number of other reactions in which C^{12} may be formed in high excitation. In particular the observation by Rasmussen *et al.*[6] of a 15-Mev gamma ray from alpha-particle bombardment of Be^9 suggested that the 15-Mev state in C^{12} has a gamma radiation width of similar magnitude to its alpha width. Barnes and Kavanagh[7] reported measurement of the threshold for producing 15.1-Mev gamma radiation in the $B^{11}(d,n)C^{12}$ reaction and Marion, Bonner, and Cook[8] measured the neutron threshold for the same reaction to correspond to 15.1-Mev excitation. Together all these measurements provide strong evidence for the existence of a level in C^{12} at 15.1 Mev that has a gamma width of similar magnitude to its alpha width. This conclusion has been verified in the studies by Hayward and Fuller, and by Garwin and Penfold, of elastic scattering of 15.1-Mev photons by carbon[9] and in the present work using the $B^{10}(He^3,p)C^{12*}$ reaction[10] by the direct observation of coincidences between protons feeding the level at 15.1 Mev and the de-excitation gamma radiations. The present paper reports studies of the de-excitation branching of this level. In addition the formation of the same level in the reaction $C^{13}(He^3,\alpha\gamma)C^{12}$ was observed but no detailed studies were carried out.

[1] Bigham, Allen, and Almqvist, Phys. Rev. **99**, 631(A) (1955).
[2] Moak, Galonsky, Traughber, and Jones (private communication).
[3] F. Ajzenberg and T. Lauritsen, Revs. Modern Phys. **27**, 77 (1955).
[4] V. K. Johnson, Phys. Rev. **86**, 302 (1952).
[5] Cohen, Mayer, Shaw, and Waddell, Phys. Rev. **95**, 664 (1954); **96**, 714 (1954).
[6] Rasmussen, Rees, Sampson, and Wall, Phys. Rev. **96**, 812L (1954).
[7] R. W. Kavanagh and C. A. Barnes, Phys. Rev. **100**, 1996A (1955); and to be published.
[8] Marion, Bonner, and Cook, Phys. Rev. **100**, 847 (1955).
[9] E. Hayward and E. G. Fuller, Phys. Rev. **106**, 991 (1957); E. L. Garwin and A. S. Penfold, Bull. Am. Phys. Soc. Ser. II, **2**, 351 (1957).
[10] Gove, Litherland, Almqvist, Bromley, and Ferguson, Bull. Am. Phys. Soc. Ser. II, **2**, 51 (1957).

Gamma radiation ascribed to ground-state transitions from a level in C^{12} at 12.78 Mev has been reported by Kavanagh and Barnes[7] in the $B^{11}(d,n)C^{12}$ reaction, and by Waddell[11] in $C^{12}(p,p')C^{12*}$. This assignment is confirmed by the present studies. In addition the magnitude of the gamma-ray width of the 7.65 level[7,12,13] is particularly interesting because of its astrophysical significance.[14] An attempt was made to observe this width but it was found too small to be observed with the present experimental arrangement.

Theoretical investigations of the levels of C^{12} have recently been made by Kurath[15] using an intermediate coupling shell model, and Glassgold and Galonsky[16] using an alpha-particle model, and their predictions are compared with the measured properties of C^{12}.

2. EQUIPMENT

A. General

The experimental apparatus used in these measurements, except for minor alterations, is the same as that described in the study of the $C^{12}(He^3,p)N^{14}$ reactions[17] and is only briefly outlined here. The target holder has been modified to include a thin heater that maintains the target at several hundred degrees centigrade and effectively reduces the rate of buildup of carbon on the target during bombardment. The elimination of this target contaminant was particularly important since the prolific reaction $C^{12}(He^3,p)N^{14}$ produces a proton group of nearly the same energy as the protons from the reaction $B^{10}(He^3,p)C^{12}$ associated with the formation of the 15.1-Mev level in C^{12} under study. The targets were 99% B^{10} isotope deposited directly on the backings by the magnetic separator at AERE Harwell to thicknesses ranging from 20 to 100 microgram cm^{-2}. Targets on tantalum, nickel, and aluminum backings were used as indicated in the description of the experiments.

B. Particle Detectors

The proton detectors were CsI crystals covered by 0.0004 inch of aluminum and optically coupled to RCA 6655 photomultipliers. One, with a solid angle of 9×10^{-3} steradian, was used to observe direct spectra and gave a resolution of 3.5%. The other subtended a solid angle of 5×10^{-2} steradian which made it more useful for coincidence studies when high counting efficiency is important, albeit with slightly poorer resolution.

C. Gamma Detectors

The gamma radiation was detected using four-inch deep, five-inch diameter NaI crystals which have previously been described.[18] These with associated shielding were mounted on arms that could be moved about a vertical axis centered on the target and were therefore always coplanar with the horizontal beam tube. When studying $(p\gamma)$ coincidences the proton counter was mounted at 90° to the beam either in this plane or perpendicular to it.

D. Electronics

The outputs of the detectors were delay line clipped and amplified using conventional circuitry and the pulse-height distributions displayed either on a 30-channel or on an 80-channel analyzer. The 30-channel instrument[19] has a dead time of ten microseconds and was used to determine absolute counting rates, while the slower 80-channel Hutchinson-Scarrot[20] type analyzer was used to study details of the spectra. The circuitry was arranged so that either one or both analyzers could display the output from one counter that was in time coincidence with counts in a voltage gate which selected any desired part of the spectrum of a second counter. Measurements made with this arrangement are later referred to as "gated" coincidence measurements. The occurrence of a coincidence was determined by a "fast" coincidence circuit[21] adjusted to a resolving time 2τ equal to 40 millimicroseconds which would gate the "slow" circuit used for pulse-height selection and measurement.

E. Calibrations

Pulse heights were measured in terms of dial divisions of a stable mercury relay type pulse generator whose output was connected to the input of the amplifier system. In Fig. 1 is the proton calibration curve for the particle counter obtained by plotting the observed pulse height against the proton energy at 90° to the beam computed from known Q values.[3] The reaction $C^{12}(He^3,p)N^{14}$ provided calibration points at 6.020 and 3.867 Mev, and the $B^{10}(He^3,p)C^{12}$ reaction to the ground state and the first two excited states provided points at 19.642, 15.572, and 12.692 Mev proton energy. By joining these points with a smooth curve a proton energy scale was established for the detector system from which energies could be obtained with an

[11] Waddell, Adelson, Mayer, and Shaw, Bull. Am. Phys. Soc. Ser. II, **2**, 181 (1957); C. N. Waddell, thesis, Radiation Laboratory, University of California (unpublished).

[12] S. F. Eccles and D. Dobansky, Bull. Am. Phys. Soc. Ser. II, **3**, 188 (1958).

[13] Cook, Fowler, Lauritsen, and Lauritsen, Phys. Rev. **107**, 508 (1957).

[14] E. J. Opik, Proc. Roy. Irish Acad. **A54**, 49 (1951); E. E. Salpeter, Astrophys. J. **115**, 326 (1952); F. Hoyle, Suppl. Astrophys. J. **1**, 121 (1954).

[15] D. Kurath, Phys. Rev. **101**, 216 (1956); **106**, 975 (1957).

[16] A. E. Glassgold and A. Galonsky, Phys. Rev. **103**, 701 (1956).

[17] Bromley, Almqvist, Gove, Litherland, Paul, and Ferguson, Phys. Rev. **105**, 957 (1957).

[18] Litherland, Paul, Bartholomew, and Gove, Phys. Rev. **102**, 208 (1956).

[19] Moody, Howell, Battell, and Taplin, Rev. Sci. Instr. **22**, 551 (1951).

[20] G. W. Hutchinson and G. G. Scarrot, Phil. Mag. **42**, 792 (1951).

[21] Bell, Graham, and Petch, Can. J. Phys. **30**, 35 (1952).

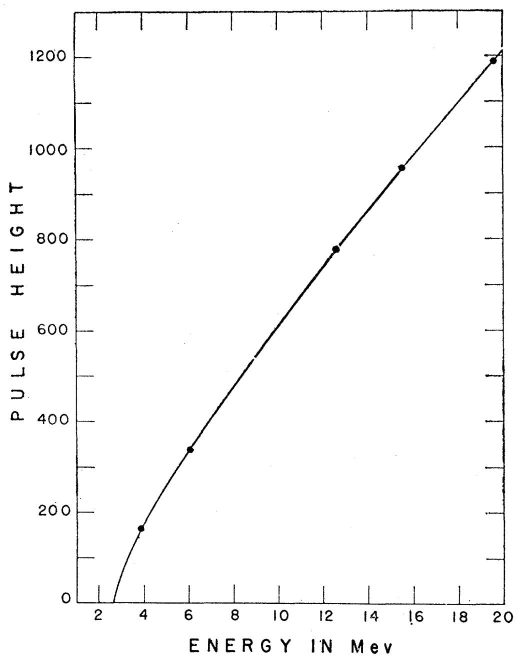

FIG. 1. The proton energy *vs* pulse-height calibration curve for the CsI particle detector covered by 0.0024 inch of aluminum. The calibration points are discussed in Sec. 2E of the text.

accuracy of ±0.10 Mev. The curve has been drawn to intercept the energy axis at a point corresponding to the energy of a proton just stopped in a 0.002+0.0004 inch aluminum foil combination which covered the CsI crystal. The computed stopping energies[22] for protons, deuterons, and alpha particles are 2.6, 3.3, and 9.6 Mev, respectively. This absorber therefore stops even the most energetic, 9.6 Mev, alpha particles from $B^{10}(He^3,\alpha)$ reactions. For some measurements the 0.002-inch foil was removed in order to study lower energy groups. These measurements also allowed unknown particle groups to be identified as protons or deuterons by comparing their computed loss of energy in the absorber with that obtained from measured changes in pulse height relative to the proton calibration groups.

The NaI gamma-ray detectors were calibrated at high energies using the reaction $B^{11}(p,\gamma)C^{12}$ and at lower energies using $C^{12}(He^3,p)N^{14*}$. These established energy points at 17.23, 12.80, 4.43, 2.31, and 1.64 Mev. Care was taken that counting rate conditions were similar and below a total counting rate of 30 000 counts per minute during calibration runs and measurement runs to avoid counting rate shifts. This was necessary because at the much greater counting rates which were readily achieved with these high efficiency detectors and $B^{10}(He^3,p)C^{12}$ reactions, the gain of the photomultipliers would increase 5% or more over that obtained at lower counting rates.

In order to obtain cross sections and to measure particle to gamma-ray branching ratios it was necessary to know the absolute efficiencies of the detectors. The absolute efficiency of the proton counter had been determined previously[17] to be 0.073%. The efficiency of the 5-in.×4-in. NaI detectors was measured for 4.43-Mev radiation by the usual coincidence technique using the reaction $B^{10}(He^3,p)C^{12*}$ (4.43 Mev) which provides an isolated proton group coincident with the 4.43-Mev gamma ray from the first excited state of C^{12}. Allowance was made for the measured angular correlation. Counting only pulses above 3.41 Mev, i.e., the total absorption peak plus the first escape peak an efficiency of 1.06% (±0.08) was obtained with the front face of the crystal at 6.2 inches from the target center. The crystal efficiency for 12.1-Mev radiation was similarly obtained by observing coincidences between the two gamma rays from the reaction $B^{11}(p,\gamma\gamma)C^{12}$ at the $E_p=0.675$-Mev resonance. An efficiency of 0.69 (±0.06)% was obtained for a 12.1-Mev radiation if only pulses above 11.08 Mev are counted. Radioactive sources of known strength provided efficiency calibrations at several lower energies.

3. RESULTS

A. Direct Spectra

Figure 2(a) is a pulse-height spectrum taken with the particle counter at 90° to the beam at a bombarding energy of 2.14 Mev. This shows proton groups corre-

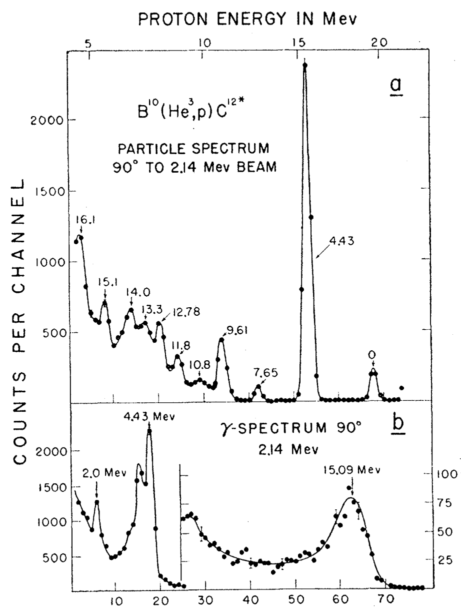

FIG. 2(a). The pulse height spectrum from the CsI particle detector covered by 0.0024 inch of aluminum to stop all alpha particles from He^3 on B^{10}. Each proton group is labeled by the excitation in Mev of the corresponding state in C^{12}. The proton energy scale is at the top of the figure. (b) The pulse spectrum from the 5-inch diameter, 4-inch deep NaI gamma-ray detector. Each group is labeled by the energy of the corresponding gamma ray.

[22] W. Whaling, *Encyclopedia of Physics*, edited by S. Flügge (Springer-Verlag, Berlin, 1958), Vol. 34.

sponding to the levels at excitations in C^{12} indicated in the figure and listed in Table I. The low-energy groups are superimposed on a continuum of protons extending out to the end point of 12.9 Mev which results from the multibody breakup, $B^{10}(He^3,p)3He^4$, that may occur either directly or as a multistep process via unstable states of C^{12}, B^9, Be^8, and N^{12}.

In order to display the low-energy groups more clearly the spectrum shown in Fig. 3 was taken with an expanded energy scale. Here in addition to the above proton groups appear a broad proton group to the 16.57-Mev level in C^{12} and a well-defined very intense group identified as due to deuterons by the amount of increase of its pulse height when the 0.002-inch absorber was removed. Assuming that the response of CsI is equal for deuterons and protons one obtains a deuteron energy of 3.88±0.10 Mev from the measurements. This is somewhat lower than the value 4.02 Mev computed from the known[3] Q of the reaction $B^{10}(He^3,d)C^{11}$ and suggests that the pulse height of a 4-Mev deuteron in CsI is a few percent smaller than that from a proton of the same energy. This effect is also observed with the 2.2-Mev deuterons from the same reaction going to the first excited state of C^{11} which are observed in the coincidence measurements discussed in another section. These results were obtained using a target of 90 microgram cm^{-2} of B^{10} on a nickel backing. Since the energy calibration was done with targets of similar thickness, the effects of the target thickness on the energy measurements are to a large extent compensated for and are much less than the ±0.10-Mev error claimed for the measurements.

Shown in Fig. 2(b) is the gamma-ray spectrum measured at 90° to a 2.14-Mev He^3 beam. Three prominent gamma rays are observed of measured energies

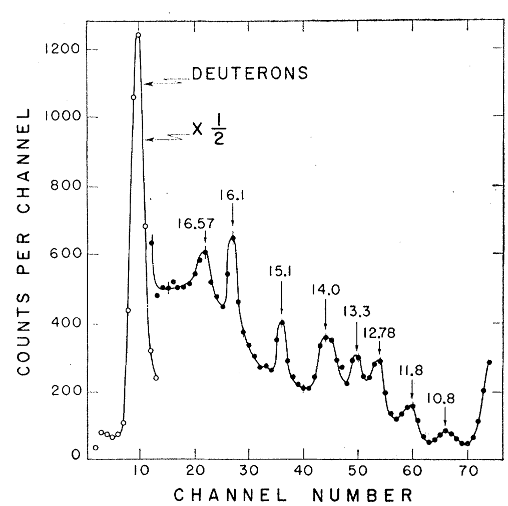

FIG. 3. The pulse-height spectrum from the CsI particle detector with twice the gain but otherwise the same conditions as Fig. 2(a). The very intense group in channel 10 was identified as deuterons from the $B^{10}(He^3,d)C^{11}$ reaction as discussed in Sec. 3A of the text.

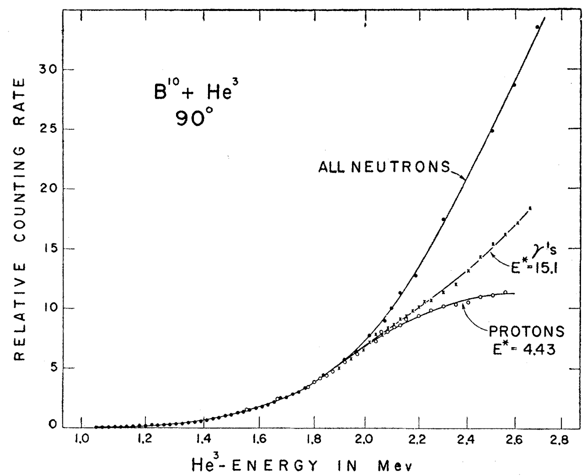

FIG. 4. The excitation curves observed at 90° to beam. The neutron detector was a BF_3 counter surrounded by paraffin[17] for which no absolute efficiency calibration was available. The differential cross sections for the particle groups and gamma radiations are listed in Table I for 2-Mev He^3 bombarding energy.

2.02±0.05, 4.43±0.05, and 15.09±0.15 Mev. The coincidence experiments described in Sec. C show that the 2.02-Mev gamma radiations results from de-excitation of the first excited state of C^{11}, the 4.43-Mev gamma ray from the first level in C^{12}, and the 15.09-Mev radiation from the lowest $T=1$ level of C^{12} at 15.10 Mev.

B. Cross Sections and Excitation Functions

The differential cross sections at 90° to the beam were determined using a Harwell target nominally 80 microgram cm^{-2} thick on aluminum backing. Its thickness was measured by the method previously described[17] of observing the energy shift of the 993-kev $Al^{27}(p,\gamma)$ resonance when the proton beam passes through the boron layer, and found to be equivalent to 26 kev of proton energy at the resonance energy. Taking a value of 223 kev cm^2 mg^{-1} for dE/dx[22] a target thickness of 116 microgram cm^{-2} is obtained in the direction of the beam. Since the target was at 45° to the beam this leads to a boron thickness of 82 microgram cm^{-2} in good agreement with the nominal value of 80 microgram cm^{-2}.

The values of the 90° differential cross sections obtained for the various particle groups using the measured target thickness are listed in Table I for a bombarding energy of 2.0 Mev. The excitation curves for the strong proton group to the 4.43-Mev state, for the 15.1-Mev gamma radiation, and for neutrons of all energies are shown in Fig. 4. The curves show a smooth rise of yield with energy over the range studied with no evidence of any resonances below 2.5-Mev bombarding energy. The proton excitation curve has been extended by Schiffer *et al.*[23] to much higher energies and

[23] Schiffer, Bonner, Davis, and Prosser, Phys. Rev. **104**, 1064 (1956).

TABLE I. Differential cross sections at 90° to 2-Mev He^3 beam.

Reaction	Excitation energy (Mev)	Relative yield (90°)	$\partial\sigma/\partial\Omega(90°)$ (mb/sterad)
$B^{10}(He^3,p)C^{12}$	0[a]	2.2	0.05
$B^{10}(He^3,p)C^{12*}$	4.43[a]	24	0.57
$B^{10}(He^3,p)C^{12*}$	7.65[a]	1	0.02
$B^{10}(He^3,p)C^{12*}$	9.60±(0.10)	5	0.11
$B^{10}(He^3,p)C^{12*}$	10.76±(0.10)	1	0.02
$B^{10}(He^3,p)C^{12*}$	11.82±(0.10)	2	0.05
$B^{10}(He^3,p)C^{12*}$	12.78±(0.10)	3	0.07
$B^{10}(He^3,p)C^{12*}$	13.37±(0.10)	4.2	0.10
$B^{10}(He^3,p)C^{12*}$	14.03±(0.10)	4.7	0.11
$B^{10}(He^3,p)C^{12*}$	15.10±(0.10)	2.9	0.07
$B^{10}(He^3,p)C^{12*}$	16.10±(0.10)	5	0.12
$B^{10}(He^3,p)C^{12*}$	16.64±(0.10)	6	0.14
$B^{10}(He^3,d)C^{11}$	0	39	0.91
		Sum=100	
$B^{10}(He^3,p\gamma)C^{12}$	4.43[a]	24	0.57
$B^{10}(He^3,p\gamma)C^{12}$	15.09(±0.15)	2	0.05
$B^{10}(He^3,d\gamma)C^{11}$	2.02(±0.05)	2.8	0.07

[a] Used for energy calibration.

their results below 2.5 Mev are in agreement with those reported here.

The 90° differential cross sections for the production of 15.1-Mev and 4.43-Mev gamma radiations are also listed in Table I. These cannot be directly compared with the cross sections for the corresponding proton groups without knowledge of the angular distributions. For the 15.1-Mev state these have been measured and found to be nearly isotropic as discussed more fully in the later section on angular distributions. Integration of the observed differential cross section of 15.1-Mev gamma radiation over 4π steradians gives a total cross section of 0.60±0.1 mb for its production at 2.0-Mev bombarding energy. Combining this result with Fuller and Hayward's[9] value of 0.69 for the ratio of gamma width to total width of the 15.1-Mev level we obtain a total cross section of 0.87 mb at 2.0 Mev for the formation of the 15.1 level in C^{12} via the $B^{10}(He^3,p)C^{12*}$ reaction.

It is of interest to compare this cross section with that of the reaction $B^{10}(He^3,n)N^{12}$ ground state which proceeds from the same compound nucleus to a final state presumed to be the analog of the 15.1-Mev level in C^{12}. The (He^3,n) reaction[24] has a cross section at 2.56 Mev of 5.2±2 mb. Using the yield curve of Fig. 4 one obtains for the (He^3,p) cross section at 2.56 Mev a value of 2.0±0.25 mb. The ratio $(He^3,n)/(He^3,p)=2.6$ (±0.8) is to be compared with the value 2.0 predicted from the charge independence of nuclear forces.[25] Similar comparisons[17] have been reported previously for the $C^{12}(He^3,n)O^{14}$ and $C^{12}(He^3,p)N^{14}$ (2.31 Mev) reactions.

[24] Ajzenberg-Selove, Bullock and Almqvist, Phys. Rev. **108**, 1284 (1957).
[25] R. K. Adair, Phys. Rev. **87**, 1041 (1952).

C. Identification of γ-emitting States

(i) General

In order to determine which of the particle groups were associated with gamma emitting levels of the residual nucleus, coincidence measurements were made using a gamma detector and a particle detector both mounted at 90° to but on opposite sides of the beam in the horizontal plane. In Fig. 5(a) is presented the spectrum of particles coincident with all gamma radiation greater than 1 Mev in energy while Fig. 5(b) shows only those particles which are coincident with gamma radiation of energy greater than 6.5 Mev. The distribution Fig. 5(a) shows three prominent particle groups of measured energies: 2.18±0.05 Mev, 5.63 ±0.10 Mev, and 15.48±0.10 Mev. Of these, only the group at 5.63 Mev is coincident with high-energy gamma radiation. These data together with the observation of three prominent gamma rays of energies 2.02 Mev, 15.1 Mev, and 4.43 Mev in the direct spectra, Fig. 2, are consistent with the energies computed from the known masses[3] for the following reactions:

$$B^{10}(He^3,d)C^{11*} \xrightarrow{\gamma} C^{11}+2.0\text{ Mev}, \quad (1)$$

$$B^{10}(He^3,p)C^{12*} \xrightarrow{\gamma} C^{12}+15.1\text{ Mev}, \quad (2)$$

$$B^{10}(He^3,p)C^{12*} \xrightarrow{\gamma} C^{12}+4.43\text{ Mev}, \quad (3)$$

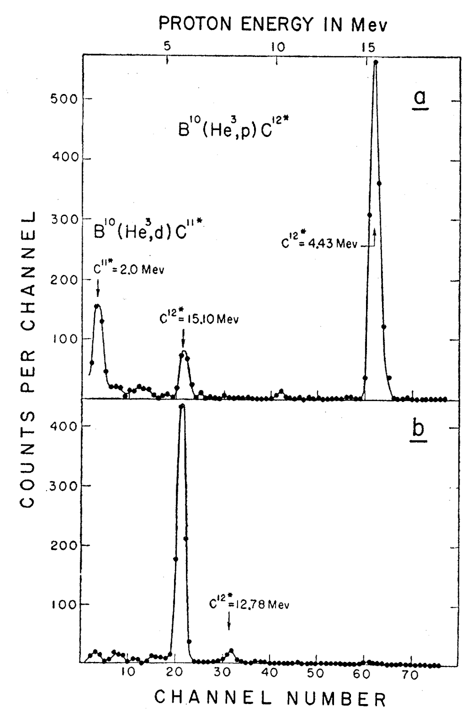

FIG. 5(a). The distribution of pulse heights of particles coincident with all gamma radiation. The groups are labeled by the excitation of the corresponding residual state. The proton energy scale is at the top of the figure. (b) The pulse-height distribution from particles coincident only with radiation above 6.5 Mev in energy.

which suggests that the 2.18-Mev particle group is due to deuterons from reaction (1) and the 5.63- and 15.48-Mev groups are due to protons from reactions (2) and (3), respectively. The weak group in channel 32 corresponds to protons of 7.8-Mev energy. Since they are coincident with radiation above 6.5 they are provisionally assigned on the basis of the data in Fig. 5 to the reaction:

$$B^{10}(He^3,p)C^{12*} \xrightarrow{\gamma} C^{12}+12.8\text{ Mev.} \tag{4}$$

These assignments are confirmed by the results of gated coincidence measurements discussed below which were made with the "slow-fast" circuitry described in Sec. 2D. The data are presented in Figs. 6, 7, and 8.

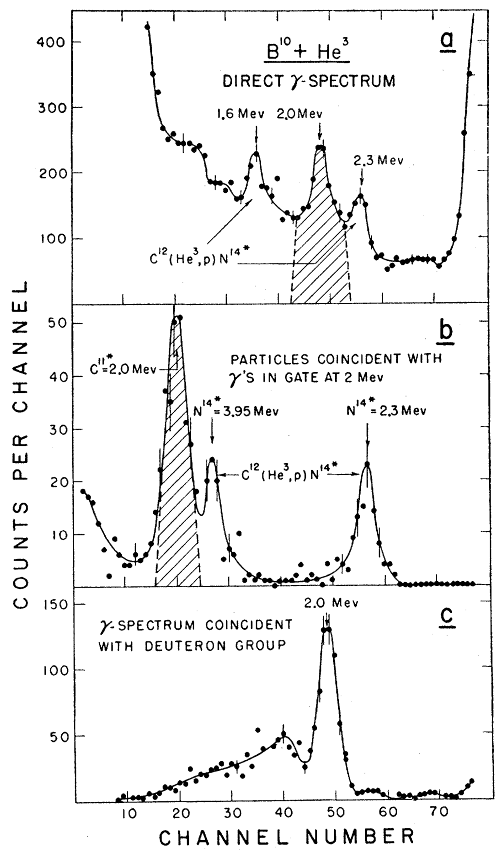

FIG. 6(a). The pulse-height distribution from the gamma-ray detector expanded to display the region near 2-Mev gamma-ray energy. The shaded area indicates the part of the spectrum selected by the voltage gate. This spectrum was taken at 90° to the beam. The peaks at 1.6 and 2.3 Mev are due to carbon contaminant on the target. (b) The pulse-height distribution from the particle detector showing only those pulses which are coincident with gamma-ray pulses in the voltage gate of (a). The two proton groups from the carbon contaminant are indicated and labeled by the corresponding excitation of the residual nucleus. The identification of the shaded group as deuterons from $B^{10}(He^3,d)C^{11*}$ is discussed in Sec. 3 C(ii) of the text. (c) The pulse-height distribution of the gamma radiation coincident with the voltage gate set as indicated by the shaded area in (b). The peak corresponds to a gamma-ray energy of 2.02 Mev. The drop in intensity below channel 20 is instrumental.

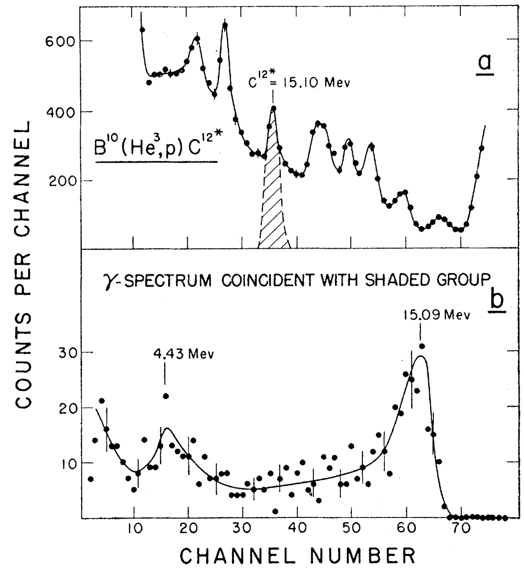

FIG. 7. (a) The particle pulse spectrum showing the voltage gate set on the proton group which corresponds to the formation of the 15.1-Mev state in C^{12}. (b) The distribution of gamma-ray pulses that are coincident with the particle pulses in the gate shown by the shaded area in (a). Each group is labeled by the corresponding gamma-ray energy.

(*ii*) $B^{10}(He^3,d\gamma)C^{11}$

The data in Fig. 6 were taken with a target which had some carbon contaminant on it that provided proton calibration groups whose change in energy could be compared with that of the suspected deuteron group when absorbers were inserted in front of the detector. The voltage gate was set to accept only gamma pulses that fell within the shaded area near 2 Mev in Fig. 6(a) and the distribution of particles coincident with counts in the gate is shown in Fig. 6(b). Both of the groups from $C^{12}(He^3,p)N^{14*}$ appear since they are coincident with the tail of the 2.3-Mev gamma radiation from the N^{14} first excited state falling within the gate, and the second state at 3.95 Mev de-excites[26] mainly via the cascade transition through the 2.3-Mev first excited state. When a gate was set to include only the shaded particle group in Fig. 6(b) the coincident gamma spectrum shown in Fig. 6(c) resulted. This result shows that the 2.02-Mev gamma radiation is coincident with the 2.18-Mev particle group as expected for reaction (1). The observed energy shift of the particle group relative to the adjacent proton calibration group when a 0.0004-inch aluminum absorber was inserted is consistent with its being due to deuterons. Assuming that deuterons and protons produce the same response in CsI one obtains from the two measurements deuteron energies of 2.14 and 2.19±0.05 Mev, respectively, which are to be compared with the value 2.23±0.05 computed using

[26] Gove, Litherland, Almqvist, and Bromley, Phys. Rev. **103**, 835(L) (1956).

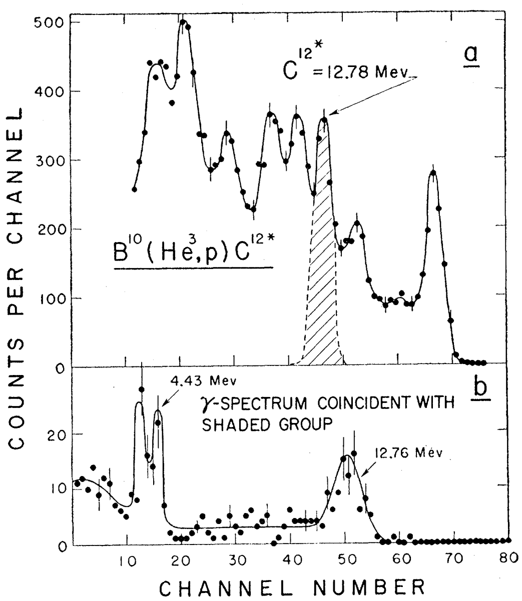

FIG. 8. (a) The particle pulse spectrum showing the voltage gate set on the proton group corresponding to the formation of the 12.78-Mev state in C^{12}. (b) The distribution of gamma-ray pulses that are coincident with the particle pulses shown by the shaded area in (a). Each group is labeled by the corresponding gamma-ray energy. The 4.43-Mev group is caused by random coincidences and by tail from the corresponding proton group falling in the gate.

2.02 Mev[27] as the excitation of the first state of C^{11}. Again the results suggest that a deuteron produces a somewhat smaller pulse height in CsI than a proton of the same energy. The measurements indicate a difference of about 7% or 100 kev in the region of 1.5-Mev particles.

(*iii*) $B^{10}(He^3,p\gamma)C^{12}$ (15.1 Mev)

Figure 7 presents the results of coincidence measurements which confirm the formation of a state in C^{12} at 15.1 Mev that emits gamma radiation. The particle gate indicated by the shaded area was set to include the proton group of 5.63-Mev energy, and the coincident gamma spectrum presented in Fig. 7(b) shows a radiation of energy measured to be 15.09 ± 0.15 Mev. The rise in the distribution at 4.43 Mev is consistent with the computed number of chance coincidences from the very intense 4.43-Mev gamma radiation from the target. The spectrum shows no evidence for 10.7-Mev gamma radiation which would result from a cascade transition from the 15.1-Mev state through that at 4.43 Mev. However, the statistical errors are such that less than 15% branching via the cascade transition can not be excluded. Consequently a gamma-gamma coincidence experiment was carried out to search for a 10.7-Mev radiation in coincidence with a 4.43-Mev gamma ray. The result shown in Fig. 11, which is discussed more fully in Sec. D on the branching of the 15.1-Mev level, shows a weak cascade branch via the 4.43-Mev state.

(*iv*) $C^{13}(He^3,\alpha\gamma)C^{12}$ (15.1 Mev)

In measurements made to study the effect of possible carbon target contamination, a very low yield of 15.1-Mev γ radiation was noticed and attributed to the reaction $C^{13}(He^3,\alpha\gamma)C^{12}$. This was verified by observing a greatly increased yield with a target enriched to 50% in the C^{13} isotope.[17] No detailed studies of this reaction were made except to observe the angular distributions of the 15.1-Mev radiation as discussed in Sec. E(*i*). The yield of 15.1-Mev gamma radiation from carbon contaminant on the B^{10} targets was negligible at all angles.

(*v*) $B^{10}(He^3,p\gamma)C^{12}$ (12.78 Mev)

Figure 8(b) shows the spectrum of gamma-rays that are coincident with the particle group corresponding to the 12.78-Mev level in C^{12}. The observation of a gamma ray of 12.8-Mev energy confirms that the level in C^{12} at 12.78 Mev emits gamma radiation. There is no evidence for an 8.33-Mev cascade transition via the 4.43-Mev state of intensity greater than 20% the ground-state transition. Again the 4.43-Mev peak has an intensity consistent with the computed chance coincidence rate. Assuming isotropic angular distributions and using the measured counter efficiencies and proton counting rate, the expected coincidence rate which would be observed if the 12.78-Mev level decayed entirely by gamma emission may be computed. The largest uncertainty is in determining the counting rate of the appropriate protons since these are superimposed on a continuum and are not clearly resolved from adjacent groups. The measured coincidence rate is 2% of the computed value which implies that for the 12.78-Mev state of C^{12} the gamma width is 2 ($\pm$1)% of the total width.

A second estimate of the value of Γ_γ/Γ of the 12.78-Mev level relative to Γ_γ/Γ for the 15.1-Mev level can be made by comparing the ratios of intensities of the two corresponding particle groups in the direct spectrum to the same ratio obtained in the coincidence spectrum, Fig. 5(b). The latter was corrected for the relative efficiencies of the gamma counter to 12.78-Mev and 15.1-Mev gamma radiation. Assuming Fuller and Hayward's value,[9] $\Gamma_\gamma/\Gamma=0.69$ for the 15.1-Mev state, a gamma width for the 12.78-Mev state equal to 1.4% of its total width is obtained subject again to the assumption of isotropic angular correlations, but in good agreement with the value 2 ($\pm$1)% obtained by the more direct method.

(*vi*) $B^{11}(He^3,p\gamma)C^{13}$

The coincidence particle spectrum Fig. 5(a) shows a weak group at 10.2 Mev which if from $B^{10}(He^3,p)C^{12*}$ would correspond to a level in C^{12} at 10.1 Mev. However its energy is that expected for the proton groups from

[27] Ajzenberg-Selove, Johnson, Rubin, and Mazari, Phys. Rev. **103**, 356 (1956).

$B^{11}(He^3,p)C^{13*}$ feeding the C^{13*} levels at 3.68 and 3.86 Mev. To test this possibility a gamma-ray spectrum in coincidence with this group was measured; it consisted of a complex of gamma rays of maximum energy 3.86 Mev and can be accounted for by the $\lesssim 1\%$ B^{11} in the target.

(*vii*) $B^{10}(He^3,p\gamma)C^{12}$ (7.65 Mev)

Apart from the well-known state at 4.43 Mev there is no evidence of any level in C^{12} below 12.78-Mev excitation with a gamma width equal to or greater than 2% of its particle width. Because Γ_γ of the 7.65-Mev state is of particular importance in astrophysics, attempts were made to set an upper limit on the ratio $\Gamma_\gamma:\Gamma$ for this state. If a 7.65-Mev ground-state transition occurred the corresponding proton group would appear in spectrum 5(b) which shows particles in coincidence with gamma radiation of greater than 6.5-Mev energy. This measurement shows zero counts in the region of the 7.65-Mev peak which allows a limit to be set for the ratio Γ_γ (ground state):Γ of $\lesssim 0.002$ assuming isotropy of the radiations. However a similar low limit on the cascade radiation via the 4.43-Mev state cannot be made from the data in Fig. 5(a) because of the tail of counts extending to lower channels from the very intense group in channel 63 corresponding to the feeding of the 4.43-Mev state. In this run the region of the 7.65-Mev peak after subtraction of background has zero ± 4 counts in it while the 4.43-Mev peak has 2346 counts. Comparison of this result with the ratio of intensities observed in the direct spectrum allows a limit on the ratio $\Gamma_\gamma:\Gamma<0.04$ to be set for the 7.65-Mev state.

A second attempt to observe the cascade transition was made by searching for gamma-gamma coincidences using two NaI crystals facing each other and the "slow-fast" circuits to allow only those counts from one crystal to be recorded that were coincident with counts in the 4.43-Mev total absorption peak in the second crystal. This measurement showed a 4.43-Mev gamma ray in the coincidence spectrum which is attributed to the feeding of the 4.43-Mev level in C^{12} by the beta decay of N^{12} formed via $B^{10}(He^3,n)N^{12}$ as well as to chance coincidences. The high-energy beta rays or their bremsstrahlung may produce pulses that fall in the 4.43-Mev gate in one crystal and the coincident gamma ray was detected in the second crystal. No evidence was found for the 3.22-Mev cascade radiation from the 7.65-Mev state; the background due to true β-γ coincidences precluded setting a limit lower than $\Gamma_\gamma:\Gamma\lesssim 0.03$. In an attempt to gain further information on this ratio the same γ-γ coincidence arrangement was used with a Pu-Be source containing 1 g of Pu mounted between the crystals. The Pu-Be source was surrounded by boron-carbide loaded paraffin to minimize the probability of neutrons from the reaction $Be^9(\alpha,n)C^{12*}$ reaching the crystals and producing true neutron-gamma coincidences. In runs totaling 90 hours duration, no evidence was found for a 3.22-Mev radiation coincident with a 4.43-Mev γ ray. Unfortunately the coincidence counting rate owing to residual true neutron-gamma coincidences and to accidental coincidences is such that no better than an upper limit of $\Gamma_\gamma:\Gamma\lesssim 0.01$ can be established for the cascade gamma radiation from the 7.65-Mev state. These results are in agreement with the observations of Kavanagh and Barnes,[7] and Eccles and Bodansky[12] who have established a limit of less than 0.1% for modes of de-excitation via gamma-ray or pair emission.

(*viii*) *Other Reactions*

No evidence was found for any level in C^{12} near 5.5 Mev as required by the α-particle model.[16] In Fig. 5 there are weak particle groups of energy less than 5 Mev that appear to be coincident with gamma radiation. Some of these may be associated with levels in C^{12}, e.g., the 16.1-Mev level is known to have a gamma width of 1.4% of its total width[3] and must contribute a small number of coincidence counts. However, contaminant reactions such as $C^{12}(He^3,p)N^{14*}$ and $O^{16}(He^3,p)F^{18}$ may also produce particle groups of less than 5-Mev energy that are coincident with gamma radiation. For this reason and because the corresponding region of excitation in C^{12} is readily accessible and has been widely studied by the $B^{11}(p,\gamma)$ and (p,α) reactions,[3] no attempt was made to investigate the low-energy particle groups with the exception of the intense deuteron groups already discussed.

D. Branching of the 15.1-Mev level in C^{12}

(*i*) $\Gamma_\gamma:\Gamma$

In order to measure the ratio of the gamma radiation width to the total width of the 15.1-Mev level in C^{12} a comparison was made between the yield of protons to the 15.1-Mev level and the yield of gamma rays from the level. For these measurements a fresh target, 80 microgram cm^{-2} of 99% isotopic B^{10} on 0.006-inch aluminum was used to minimize carbon contamination. The bombarding energy was 2.0 Mev. The absolute efficiency of the proton counter had been determined as described previously[17] to be 0.073%; the absolute efficiency of the gamma detector for 15.1-Mev radiation was obtained from the measured efficiency at 12.1 Mev by assuming that the rate of change of efficiency is that given by the calculations of Wolicki, Jastrow, and Brooks.[28] Their calculations pertain to all interactions in the crystal while our measurements of efficiency use only the high-energy fraction of the pulse-height spectrum because the low-energy part is masked by other low-energy gamma rays. The part of the spectrum used is indicated by the cross-hatching in Fig. 9. The lower

[28] Wolicki, Jastrow, and Brooks, Naval Research Laboratory Report NRL-4833 (unpublished).

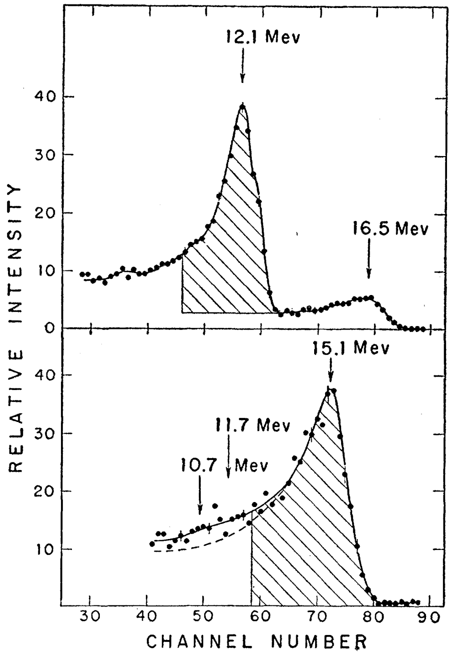

FIG. 9. The upper curve shows the pulse-height spectrum from the 16.5- and 12.1-Mev gamma radiations produced by 675-kev protons on B^{11}. The lower curve is the pulse spectrum due to 15.1-Mev radiation from He^3 on B^{10}. The expected positions of peaks due to 10.7- and 11.7-Mev radiations are indicated. The shaded area has a lower cutoff at 0.82 of the peak position in each case and represents the fraction of the spectra used in the efficiency measurements discussed in Sec. 3 D(ii).

limit represents the fraction 0.82 of the peak pulse height. Since the two spectra are very similar in shape this is believed to correspond to very nearly the same fraction of the total number of interactions in each case, and hence the calculation of Wolicki *et al.* can be applied to extrapolate the efficiency from 12.1 to 15.1 Mev. In any case the extrapolation is very small; the results yield 0.93% at 12.1 Mev, and 0.97% at 15.1 Mev for the fractions of the spectra indicated in Fig. 9 with the crystal face at 6.2 inches from the target.

To obtain the total rate of formation of the 15.1-Mev state in C^{12} from the measured 90° yield of protons requires a knowledge of the angular distributions. For this reason spectra were taken at 0°, 45°, 90°, and 148° in the laboratory system using the 30-channel analyzer to view only the region of the proton spectra of interest. The results given in Fig. 10 show the distribution of the protons associated with the 15.1-Mev level to be nearly isotropic and that within the accuracy claimed for the branching measurement the total cross section is 4π times the differential cross section at 90°. This measurement was done using an 80 microgram cm^{-2} B^{10} target on 0.0005-inch aluminum to permit the protons to be observed through the backing. The angular distribution of the 15.1-Mev radiation was also observed and found to be of the form $W(\theta)=1+0.07P_2(\cos\theta)$.

Using the measured angular distributions together with the counter efficiencies quoted above and the observed 90° yields of protons and gamma radiation from the same target a total yield of 15.1-Mev radiation equal to 0.75 ($\pm$0.20) that of the rate of formation of the 15.1-Mev state is obtained. The major uncertainty in this value is the estimate of the counts in the peak corresponding to the proton group feeding the 15.1-Mev level in C^{12} since it is superimposed upon an intense continuum of protons from the reaction $B^{10}(He^3,p)3He^4$ which may occur either as a multistep process or directly.

(*ii*) $\Gamma_{10.7}:\Gamma_{15.1}$

The gamma-ray branching of the 15.1-Mev level via cascade transitions through the 4.43-Mev state was obtained by observing gamma-gamma coincidences using two 5-in. diameter 4 in. deep NaI crystals. To minimize the chance coincidence rate a reduced beam intensity was employed and the crystals were moved in to 7.5 cm from the target. This geometry had the advantage that the detectors each subtended 40° at the target thus attenuating the effects of angular correlations so that a fair measure of the branching ratio was obtained. Measurements were made in two geometries; first with both crystals at 90° to the beam, and second with one crystal at 90° and one at 45°. In both cases the crystals were on opposite sides on the beam and coplanar with it.

A voltage gate was set to accept from one crystal pulses corresponding in size to the total absorption and first escape peaks from the 4.43-Mev radiation. The spectrum from the second crystal coincident with pulses in the gate is shown in Fig. 11. Here appear gamma rays of energy 10.7 Mev and 4.43 Mev and a low intensity tail extending out to 15.1 Mev. All of the 15.1-Mev tail and some of the 4.43-Mev radiation is accounted for by the computed chance coincidence rate. A contribution to the 4.43-Mev peak is also made by beta-gamma coincidences as discussed in Sec. C (vii). The 10.7-Mev radiation, however, can only be ascribed to the transi-

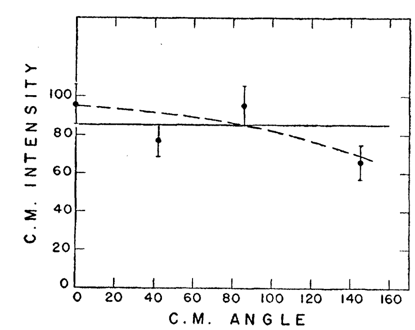

FIG. 10. The angular distribution of the protons that correspond to the formation of the 15.1-Mev state in C^{12}. The He^3 energy is 2.0 Mev. The distribution is near isotropic. Integration of either the dashed curve or the solid curve yields a total cross section equal to 4π times the differential cross section at 90° to the beam.

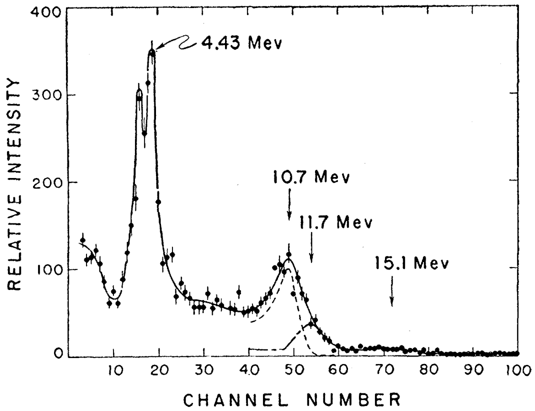

FIG. 11. The pulse distribution of gamma radiation that is coincident with gamma radiation of 4.43-Mev energy from He^3 and B^{10}. The 10.7-Mev peak is due to the 3.1% cascade branch from the 15.1-Mev state to the 4.43-Mev level. A small yield of 11.7-Mev radiation due to the transition from the 16.1-Mev state to the 4.43-Mev level is also apparent. All of the tail extending out to 15.1 Mev and most of the 4.43-Mev peak is due to chance coincidences.

tion between the 15.1 and 4.43-Mev states. The shoulder on the upper edge of the 10.7-Mev gamma-ray peak is attributed to the 11.7-Mev transition from the 16.1-Mev state to that at 4.43 Mev. The intensity of the 11.7-Mev gamma ray is consistent with rough estimates that can be made by assuming that the formation probabilities of the 16.1- and 15.1-Mev states are in the ratio of the intensities of the corresponding proton groups at 90° and using the known fact that 1.4% of the decays of the 16.1-Mev state give an 11.7-Mev radiation.[3] The major uncertainty of the measurement is in the subtraction of the 11.7-Mev contribution from the observed data to obtain the yield of 10.7-Mev radiation.

If a fraction x of the total gamma-ray de-excitations of the 15.1-Mev state gives the 10.7-4.43 cascade radiations, then it is easily shown that the ratio of 10.7-Mev quanta to 15.1-Mev quanta is:

$$\frac{x}{1-x}=\frac{N_c}{N_{15.1}}\frac{\epsilon_{15.1}}{\epsilon_{10.7}}\frac{1}{\epsilon_{4.43}},$$

where N_c is the true coincidence rate, $N_{15.1}$ is the counting rate of 15.1-Mev quanta and ϵ is the efficiency of the detectors for the indicated energies. The ratio $\epsilon_{15.1}/\epsilon_{10.7}$ was obtained using the calculations of Wolicki *et al.*[28] as discussed above. The efficiency, 4.43, of the detector gate set to detect the 4.43-Mev radiation was experimentally determined, using the $B^{11}(p,\gamma\gamma)C^{12}$ reaction at the 0.675-Mev resonance. Analysis of these data gives the intensity of the 10.7-Mev transition to be $3.1(\pm0.6)\%$ of the ground-state transition. If one assumes negligible 11.7-Mev radiation and includes all the counts in the 10.7-Mev peak an upper limit to the branching of 4% is obtained. The result was the same for the 90° and 45° angle of observation.

E. Angular Correlations

(*i*) 15.1-Mev γ *Ray*

In this work no study of the angular distributions of the particle groups has been undertaken except that already mentioned in connection with the branching of the 15.1-Mev state. Angular distributions with respect to the beam of the 15.1-Mev gamma radiation measured at the 2.13-Mev incident energy gave a result of the form $1+0.07(\pm0.02)P_2(\cos\theta)$ and at 2.51 Mev the form $1+0.04(\pm0.02)P_2(\cos\theta)$. These are illustrated in Fig. 12. The ratio of 0° yield to 90° yield was also checked at 2.01 Mev and 2.26 Mev. The conclusion is that over this energy range there is no significant change in the form of the angular distribution with bombarding energy and therefore the 90° yield curve of Fig. 4 is a good representation of the variation with energy of the

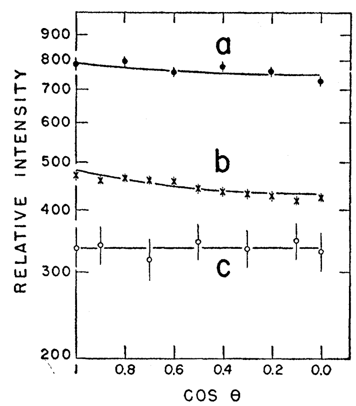

FIG. 12. Angular distribution of the 15.1-Mev gamma radiation. The angle θ is between the beam and the gamma detector. (a) is at 2.51-Mev He^3 energy; the solid curve is of the form $P_0+0.04 P_2(\cos\theta)$. (b) is at 2.13-Mev He^3 energy; the solid curve is of the form $P_0+0.07P_2(\cos\theta)$. (c) is a triple correlation measurement in which the 15.1-Mev gamma radiation coincident with particles emitted at 90° to the beam was detected. The two counters and the beam were coplanar.

total formation cross section of the 15.1-Mev state in C^{12} over the region shown.

Also shown in Fig. 12 is the result of a triple correlation experiment in which protons feeding the 15.1-Mev level were detected in the particle counter at 90° to the beam and the yield of gamma radiation coincident with these protons observed as a function of the angle with the beam. The result is an isotropic distribution to within ±3%. The counters and beam were coplanar. Since an isotropic correlation may arise in several ways, there is no information obtained from this measurement about the spin of the 15.1-Mev state.

The angular distribution of the 15.1-Mev radiation from $C^{13}(He^3,\alpha\gamma)C^{12}$ also was observed at $He^3=2.26$ Mev and found to be of the form $1-0.13P_2(\cos\theta)$. No variation in the 0° to 90° ratio was detected between 2.02- and 2.26-Mev He^3 energy.

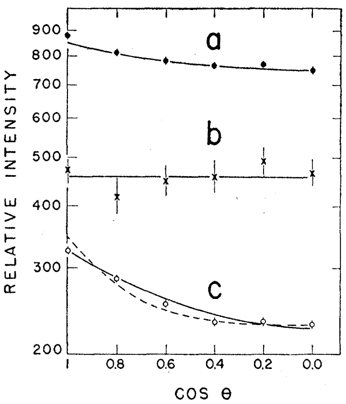

FIG. 13. Angular correlations of the 4.43-Mev gamma radiation at 2.13-Mev He^3 bombarding energy. The angle θ is between the beam and the gamma-ray detector. (a) is an angular distribution about the beam; the solid curve is of the form $1+0.08P_2(\cos\theta)$. (b) is a triple correlation measurement made with the same arrangement of counters as in Fig. 12(c). (c) is a triple correlation measurement made with the proton counter at 90° to the plane containing the beam and the gamma-ray detector; the solid curve is of the form $1+0.25P_2(\cos\theta)$; the dashed curve is $1+0.25P_2(\cos\theta)+0.1\ P_4(\cos\theta)$.

(ii) 4.43-Mev γ *Ray*

The angular distribution of the 4.43-Mev radiation with respect to the beam at 2.13-Mev incident energy is shown in Fig. 13, to be of the form $1+0.08(\pm0.02)\times P_2(\cos\theta)$. A triple correlation measurement similar to that described above made with the counters and beam coplanar gave an isotropic result to $\pm3\%$. A second triple correlation experiment was performed with the particle counter at 90° to the plane of the beam and the axis of the gamma detector. The result shown in Fig. 13(c) is strongly anisotropic. The solid curve is of the form $1+0.25(\pm0.02)P_2(\cos\theta)$. The dashed curve illustrates the effect of a small P_4 term which might be expected in this case for a $2+\rightarrow0+$ transition and has the form $1+0.25P_2(\cos\theta)+0.1P_4\times(\cos\theta)$; this shows that a P_4 term of less than 10% Po is not excluded by the observations. The main reason for carrying out these triple correlation measurements was to permit the efficiency of the NaI gamma-ray detectors to be determined from the ratio of the measured coincidence rate averaged over all angles to the measured counting rate of the particle group feeding the 4.43-Mev state.

4. DISCUSSION

A. Gamma-ray Branching

(i) *The* 15.1-Mev *State*

A 1+, $T=1$ assignment to the 15.1-Mev state is strongly suggested by all available experimental evidence; in particular the studies of the inelastic scattering by carbon of photons[9] and charged particles[11] make it seem certain that it is the lowest $T=1$ state in C^{12} and hence the analog of the ground state of B^{12} which has been shown[7] to be 1+. This assignment is assumed in the discussion that follows and is supported by the present He^3 studies.

The measurements show that the 15.1-Mev state has a gamma radiation width that is $75(\pm20)\%$ of the total width. Of this gamma radiation, $3.1(\pm0.6)\%$ is via a cascade branch through the 4.43-Mev state and the remainder to the ground state. The strength of the ground-state branch is in agreement with the results of the photon scattering measurements[9] which give for it the fraction $69(\pm7)\%$ of the total width. Hayward and Fuller[9] did not observe the cascade branch and put an upper limit of 10% contribution from radiation near 11 Mev. However the 10.7-Mev cascade radiation was observed by Waddell[11] in the $C^{12}(p,p')C^{12*}$ reaction. At 80° to the proton beam the intensity of the 10.7-Mev radiation was $9(\pm1.5)\%$ of the 15.1-Mev radiation. Since the angular distribution of the radiation from $C^{12}(p,p')C^{12*}$ is not known an integration over 4π steradians can not be carried out to obtain the branching ratio to compare with the value reported here which was obtained in a geometry that minimized angular effects. Possible reasons for the disparity in the results are discussed more fully below. Garwin and Penfold[9] report the cascade transition is 3.5% the intensity of the ground-state branch in agreement with our results.

Kurath[15] using an intermediate coupling shell model has computed the gamma radiation widths for the transitions from the 15.1-Mev state to both the ground state and the 4.43-Mev levels as a function of the parameter a/K which measures the relative strengths of the spin orbit and central forces assumed. In Fig. 14 the computed branching is compared with the experimental result and agreement obtained for values of a/K from 3.6 to 5.3. These values of a/K may be compared to those obtained from the measured width[9] of the ground-state transition which gives a/K in the range 5.5 to 6.5. A value 5.4 of a/K represents a reasonable compromise between these results; this value is appropriate for the mass-12 region as demonstrated by Kurath. The intermediate coupling shell model therefore appears to give a fair quantitative description of the radiation widths of the 15.1-Mev state.

Using this model with $a/K=5.4$ an $E2$ width of 1.1% of the $M1$ width for the 10.7-Mev transition is predicted. Assuming, therefore, that the ratio $E2:M1$ is much less

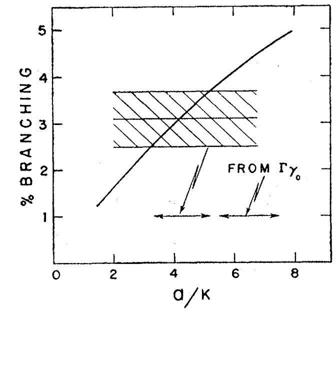

FIG. 14. The values of the intermediate coupling parameter a/K that are consistent with the measured branching of the 15.1-Mev state. The solid curve is obtained from the calculations of Kurath[15]; the cross-hatched area defines the limits set by the measurements. The range of values of a/K consistent with the measured width of the ground-state transition[9] is also indicated.

TABLE II. Comparison of the properties of states in C^{12} in the region of 12–18 Mev excitation that has observable radiation widths. Γ is the total width. $\gamma^2(\alpha_0)$ and $\gamma^2(\alpha_1)$ are reduced widths for alpha-particle emission to the ground state and first excited state of Be^8, respectively. γ_p^2 is the reduced proton width. $\Gamma(\gamma_0)$ and $\Gamma(\gamma_1)$ are radiation widths for transitions to the ground state and first excited state. J = total angular momentum, π = parity, and T = isobaric spin of the C^{12} state. The last five columns list the widths in single particle units which were computed to be 770 kev for alpha particles, 1940 kev for protons, $0.021E^3$ for $M1$ radiation, and $0.578\ E^3$ for $E1$ radiation.

Level energy Mev	Γ kev	$\gamma^2(\alpha_0)$ kev	$\gamma^2(\alpha_1)$ kev	γ^2_p kev	$\Gamma(\gamma_0)/E^3$	$\Gamma(\gamma_1)/E^3$	$J\pi T$	$\frac{\gamma^2(\alpha_0)}{\hbar^2/\mu a^2}$	$\frac{\gamma^2(\alpha_1)}{\hbar^2/\mu a^2}$	$\frac{\gamma_p^2}{\hbar^2/\mu a^2}$	$\frac{\Gamma(\gamma_0)}{\Gamma_w}$	$\frac{\Gamma(\gamma_1)}{\Gamma_w}$
12.78	$\lesssim$2.2		$\lesssim$3.7		$\lesssim$0.021		(1+)0		$\lesssim$0.49%		$\lesssim$100%	
15.10	0.079		0.0071		0.016	0.0014	1+1		0.009%		76%	7%
16.10[a]	5.00	0.016	1.30	30	<0.0019	0.044	2+1	0.002%	0.17%	1.5%		210%
16.57[a]	322.	$\lesssim$0.008	27	540	<0.0003	0.0084	2−1	<0.001%	3.5%	28%		1.5%
17.23[b]	1270	7.00	190	0.010	0.008	0.010	1−(0)	0.9%	25%	0.05%	1.4%	1.7%

[a] F. Ajzenberg and T. Lauritsen, Revs. Modern Phys. **27**, 77 (1955).
[b] Dearnaly, Dissanaike, French, and Jones, Phys. Rev. **108**, 743 (1957).

than unity it can be shown that the angular distributions of the 15.1-Mev radiation and 10.7-Mev radiation from either the $C^{12}(p,p')C^{12*}$ or the $B^{10}(He^3,p)C^{12*}$ reactions will in fact be very different from each other unless they are accidentally isotropic. The 1+ character of the 15.1-Mev state restricts the angular distributions to the form $1+a_2P_2(\cos\theta)$. The values of the a_2 coefficients themselves cannot be computed without knowledge of the angular momenta involved in the reactions, but the ratio $a_2(15.1\text{ Mev})/a_2(10.7\text{ Mev})$ depends only on the spins and multipole mixtures involved in the gamma transitions. The transition to the 0+ ground state is pure $M1$, leaving the multipole mixture of the transition to the 2+ state at 4.43 Mev as the only unknown parameter. In Fig. 15 the ratio of the a_2 coefficients[29] is plotted as a function of the multipole mixture. This shows that for $E2$ widths small relative to $M1$ widths, the 15.1-Mev radiation has a P_2 term in its angular distribution that is many times greater than that for the 10.7-Mev radiation and may be of opposite sign. The relative intensities at one angle, therefore, will differ considerably from the true branching ratio. This effect probably accounts for the discrepancy between the results of Waddell[11] and the present work. The value of the multipole mixture could

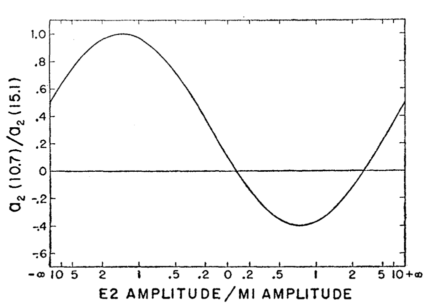

FIG. 15. The computed ratio of the a_2 coefficients of the 10.7-Mev radiation to that of the 15.1-Mev radiation as a function of the multipole mixture in the 10.7-Mev gamma radiation. The angular distributions are each assumed normalized to the form $1+a_2P_2(\cos\theta)$.

[29] Computed using Sharp, Kennedy, Sears, and Hoyle, Chalk River Report CRT-556 (unpublished).

be determined by a measurement of the ratio of a_2 coefficients but the NaI scintillation detectors used can not resolve the weak 10.7 radiation in the presence of the strong 15.1-Mev branch except in the coincidence measurement. This measurement involves a quadruple correlation with the second radiation unobserved and its angular correlation can not be interpreted without knowledge of the angular momenta in the various channels and of J values of the compound states. Therefore no attempt was made to measure angular effects.

The properties of the 15.1-Mev state are compared with other states that de-excite by gamma emission in Table II. The exceptionally small alpha-particle width of this level reflects the effectiveness of the isobaric spin selection rule which forbids alpha-particle emission and is evidence that the amount of $T=0$ admixture in this state is extremely small compared with neighboring $T=1$ states.

(*ii*) *The* 12.78-Mev *State*

The energy of this state is 2 Mev below the excitation of 15 Mev estimated for the lowest $T=1$ state based on the masses of N^{12} and B^{12} and hence it should be a $T=0$ state for which alpha-particle decay is allowed. Moreover its breakup into three alpha particles yields an energy release of 5.16 Mev which is sufficient for it to de-excite to the 2+ first excited state of Be^8 as well as the ground state. It is therefore somewhat surprising to find that this level de-excites 2% of the time via gamma-ray emission. The fact that gamma-ray de-excitation is observed in competition with alpha-particle breakup suggests a large gamma-ray width and most likely a dipole transition to the 0+ ground state. Thus the spin is probably 1. This is supported by the fact that a higher spin would favor a transition, which is not observed, to the $J=2+$ state at 4.43 Mev. A 1− assignment requires an isobaric spin forbidden $E1$ transition to the ground state while a 1+ requires a forbidden $M1$ transition.[30] The latter assignment seems more likely because conservation of spin and parity then rules out alpha decay to the ground state of Be^8 and

[30] G. Morpurgo, Phys. Rev. **110**, 721 (1958).

symmetry considerations inhibit direct breakup into three alpha particles leaving decay to the 2+ level at 2.94 Mev in Be^8 as the most likely mode of alpha-particle emission. This might be tested experimentally by observing alpha particles in coincidence with the proton group feeding the 12.78-Mev state. It has not been attempted and would be difficult to interpret owing to the superposition of the proton group on a continuum presumably from four-body breakup of the compound state, N^{13}, into a proton and three alpha particles. However there is experimental evidence from photodisintegration studies[31] that the alpha decay of this state proceeds only through Be^8 at 2.94-Mev excitation.

Taking the assignment 1+ favored by the available data we compute the single particle estimate[32] for the gamma-ray width $\Gamma_\gamma = 44$ ev for an $M1$ transition. Combining this with our measured value of 2% for the gamma-ray branch we obtain an estimate of the order of magnitude of the alpha-particle width, $\Gamma_\alpha = 2200$ ev for the 12.78-Mev state. Assuming decay via the 2.94-Mev state of Be^8 and an interaction radius of 4.5×10^{-13} we obtain the reduced alpha-particle width, $\gamma_\alpha{}^2 = 3.7$ kev which can be compared with the single particle unit of $\hbar^2/\mu a^2 = 0.77\times10^3$ kev. Usually measured alpha-particle widths are of the order of 1% of the single particle unit[33] and the obtained value of 0.5% is not uncommon. If, however, one allows a factor[30] of 100 for the isobaric spin inhibition of the gamma-ray transition, then the obtained alpha width becomes 0.005% of a single particle unit, which is unusually small.

The large value of $\Gamma_\gamma : \Gamma_\alpha$ favors a 1+ assignment to the 12.78-Mev state but the reason for the unusual inhibition of the alpha particle width is not clear. It has been shown by Christy[34] that any alpha-particle model state of C^{12} which is 1+ can not decay to either the ground state or first excited state of Be^8 and hence would be expected to have a large $\Gamma_\gamma : \Gamma_\alpha$ ratio. However, the lowest 1+ state predicted by the alpha-particle model[16] is above 20-Mev excitation, so this description does not appear to apply to the 12.78-Mev state.

B. Level Structure of C^{12}

(i) General

The energy and other properties of the state at 15.1-Mev excitation identified it as the $T_z = 0$ member of the isobaric triplet comprising this state and the ground states of N^{12} and B^{12}. Consequently all the ten states of lower excitation shown in the level diagram, Fig. 16, have $T=0$. Available experimental data permit the assignment of the indicated spins and parities to six of these states.

The 1+ assignment to the 12.78-Mev state has already been discussed in detail. The broad state at 10.1 Mev is not observed in the $B^{10}(He^3,p)C^{12}$ reaction possibly owing to its large width, but has been studied in the beta decay of B^{12} by Cook *et al.*[13,35] and assigned 0+. The electron scattering measurements have been interpreted to suggest 2+ for the 9.61-Mev level[36] in disagreement with the $B^{11}(d,n)C^{12}$ stripping results[37] which indicate negative parity for this state. It has been shown, however, by Ferrell and Visscher[38] that a 1− assignment may be in accord with the electron scattering data and can not be ruled out. The properties of the three lowest levels have been thoroughly investigated in a number of experiments[3] which strongly support the indicated assignments.

(ii) *Alpha-Particle Model*

The application of the alpha-particle model to C^{12} has been discussed in a paper by Glassgold and Galonsky.[16] This model satisfactorily correlates the ground state, the 2+ first excited state, 0+ level at 7.65 and the level at 9.61 with properties either 1− or 2+. This

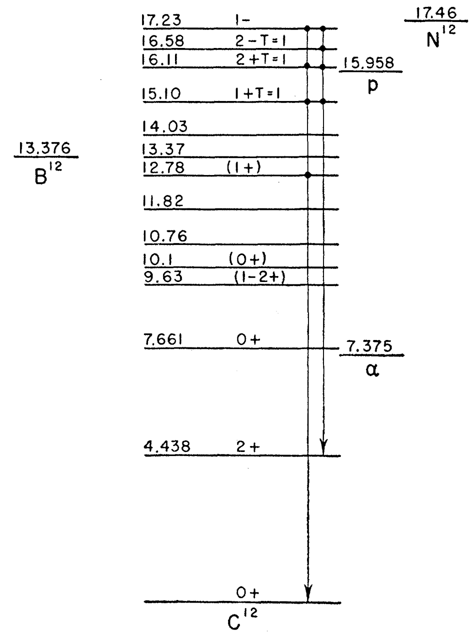

FIG. 16. The experimental level structure of C^{12}. The assignments are taken from reference 3 except for those levels discussed in the text.

[31] D. L. Livesey and C. L. Smith, Proc. Phys. Soc. (London) **66**, 689 (1953); J. L. Need, Phys. Rev. **99**, 1356 (1955).

[32] J. M. Blatt and V. F. Weisskopf, *Theoretical Nuclear Physics* (John Wiley & Sons, Inc., New York, 1952), p. 627.

[33] R. W. Hill, Phys. Rev. **90**, 845 (1953); J. R. Cameron, Phys. Rev. **90**, 839 (1953); D. H. Wilkinson, *Proceedings of the Rehovoth Conference on Nuclear Structure*, edited by H. J. Lipkin (North-Holland Publishing Company, Amsterdam, 1958), Chap. IV.

[34] R. F. Christy (private communication).

[35] Cook, Fowler, Lauritsen, and Lauritsen, reference 13 and quoted by T. Lauritsen and F. Ajzenberg-Selove (to be published).

[36] J. H. Fregeau and R. Hofstadter, Phys. Rev. **99**, 1503 (1956); R. Hofstadter and D. G. Ravenhall, quoted by D. H. Wilkinson, reference 32.

[37] A. Graue, Phil. Mag. **45**, 1205 (1954); Maslin, Calvert, and Jaffee, Proc. Phys. Soc. (London) A69, 754 (1956).

[38] R. A. Ferrell and V. M. Visscher, Phys. Rev. **104**, 475 (1956).

correlation fixes the three arbitrary parameters of the model and the positions of other levels are then computed. Its weakest points are: (i) it predicts a 3− level at 5.5-Mev excitation which has never been observed, and (ii) it can not account for a $J=1$ level at 12.78 Mev and indeed predicts no 1+, $T=0$ levels below 20 Mev.

(iii) *The Intermediate Coupling Shell Model*

The experimentally observed level structure of C^{12} may be compared with that computed by Kurath[15] using an intermediate coupling shell model. This computation predicts only five $T=0$ states lower than the first $T=1$ state which is predicted correctly near 15 Mev. The observed additional five $T=0$ states may be attributed to configurations not included in the model used, such as states arising from the excitation of nucleons out of the $1p$ shell. These states may have odd parity (single nucleon removed from p shell) or even parity (two nucleons removed from p shell) and the latter will interact with the states of the same J given by the model. Therefore the energy values computed without including these interactions may differ considerably from the true excitations and close correspondence to the experimental values can not be expected without more detailed calculations. The 1+ state observed at 12.78 Mev may be associated with the 1+ level predicted just below 14 Mev by Kurath, and the 0+ state at 10.1 Mev with that predicted at 12 Mev. Only the 4+ state then remains to be assigned and experiment rules out all states below 10.76 Mev thus favoring the scheme with the value of $L/K=5.5$ shown in Fig. 15(b) of Kurath's paper. This puts the 4+ state near 13 Mev and it would be of considerable interest if a $J=4$ state could be identified in this region. In addition this scheme correctly puts the lowest $T=1$, $J=1$ state near 15 Mev with a second $T=1$, $J=2$ state slightly higher and remarkably well describes the gamma-ray branching of the 15.1-Mev level as already discussed.

C. SUMMARY

The bombardment of B^{10} by 2-Mev He^3 ions results in the formation of a large number of excited states of C^{12} and C^{11} via the reactions (He^3,p) and (He^3,d). At 90° to the beam the (He^3,d) ground-state reaction accounts for 39% and the (He^3,p) reaction to the 4.43-Mev state for 24% of the summed yield of the proton and deuteron groups. The reason for the strong favoring of these two residual states is not known but it is also observed at lower bombarding energies[1,2] and other angles to the beam. The ratio of the (He^3,n) ground-state cross section to the analog (He^3,p) cross section is in agreement with the value computed assuming charge independence of nuclear forces.

An anomalously large ratio of gamma-ray width to alpha-particle width is observed for the 12.78-Mev state in C^{12} which suggests the properties 1+. No other alpha-particle unstable $T=0$ state is found with similar properties. The measured branching of the 15.1-Mev state is in accord with the predictions of the intermediate coupling shell-model predictions. Using the parameters $a/K=5.4$ and $L/K=5.5$ this model appears to have considerable validity in describing the properties of C^{12}.

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