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STATES IN $^{15}\text{O}$ AND $^{14}\text{N}$ FROM REACTIONS INDUCED BY $^{3}\text{He}$ ON $^{12}\text{C}$ AND PROTONS ON $^{14}\text{N}$, AND IN $^{13}\text{N}$ AND $^{13}\text{C}$ FROM $^{10}\text{Be}$ ($^{3}\text{He}$, $p\gamma_{15.1})^{12}\text{C}$ AND $^{11}\text{B}$ (d,$n\gamma_{15.1})^{12}\text{C}^{*}$.

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STATES IN O\textsuperscript{15} AND N\textsuperscript{14} FROM REACTIONS INDUCED BY He\textsuperscript{3} ON C\textsuperscript{12} AND PROTON ON N\textsuperscript{14}, AND IN N\textsuperscript{13} AND C\textsuperscript{13} FROM B\textsuperscript{10}(He\textsuperscript{3},p)\gamma\textsubscript{15.1}C\textsuperscript{12},\textsuperscript{*} AND B\textsuperscript{11}(d,n)\gamma\textsubscript{15.1}C\textsuperscript{12},\textsuperscript{*}

by

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A THESIS SUBMITTED IN PARTIAL FULFILLMENT OF THE REQUIREMENTS FOR THE DEGREE OF DOCTOR OF PHILOSOPHY

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PART ONE

States in $^{15}O$ and $^{11}N$ from Reactions

Induced by $^{4}He$ on $^{12}C$ and Protons on $^{11}N$
I. INTRODUCTION

An understanding of the reaction mechanism of many of the $\text{He}^3$ induced reactions is still in a qualitative state. Attempts at interpretation of most of the experimental results have been far from successful as compared with those of reactions which are unmistakably typical of compound nucleus formation or direct interaction. There are two immediate explanations which can be arrived at from a very general point of view. First, because of the fact that the mean binding energy of $\text{He}^3$ in compound systems in the light nuclei is high ($\sim 17 \text{ MeV}$) one would expect in general, even at low bombarding energies, that the level densities and level widths of the compound systems would be fairly large and consequently that the studies of individual resonance reactions would be rather difficult and in some cases, even impossible. Secondly, by analogy with the well known $(d,n)$ and $(d,t)$ or $(p,d)$ reactions, it seems likely that the $\text{He}^3$ induced reactions with transfer of a single nucleon such as the $(\text{He}^3,d)$ and $(\text{He}^3,\alpha)$ reactions proceed mainly via direct interactions. The more complex reactions such as $(\text{He}^3,n)$, $(\text{He}^3,p)$, or $(\text{He}^3,t)$ with transfer of two nucleons might be expected to have compound nucleus formation as the dominant reaction mechanism with direct interactions playing a subsidiary role. It is the very fact that more than one reaction mechanism can take place simultaneously in many of the $\text{He}^3$ induced reactions which makes the analysis of the experimental results more difficult and, in general, unprofitable, since for these cases one has to take into account the interference between the corresponding amplitudes of the two reaction mechanisms, and hence the number of unknown parameters usually exceeds
the number of input data.

It is part of the purpose of the present work to investigate the He$^3$ induced reactions on C$^{12}$ in the transition energy region where both compound nucleus formation and direct interaction may occur, first, to determine if possible which reaction mechanism is more important and, second, once the reaction mechanism has been ascertained, to obtain information on nuclear states reached by the reactions. In the 2 to 3.5 MeV range of He$^3$ energies, the experimental results give evidence that compound nucleus formation is important, and it is one of the purposes of the present work to see how far one can go in analyzing the experimental results by assuming pure compound nucleus formation as the reaction mechanism. In order to accomplish this purpose, one would like to obtain as much information as possible about all the particle channels with appreciable partial widths. Nearly all charged particle outgoing channels for He$^3$-induced reactions on C$^{12}$ have been studied in some detail. The total neutron cross section of $^1H(p,n)H^{11}$ was also measured. A knowledge of the total cross section is sometimes essential in the analysis of many overlapping resonances because of the fact that there is no interference effect among closed situated levels in the total cross sections. The results of these reactions will be presented in the following chapters.

$^1H$ is the residual nucleus in C$^{12}$(He$^3$,p) reactions. The properties of $H^{11}$ nucleus have long been of theoretical interest. A number of shell model calculations$^{2-5}$ have been made of the level spectrum as well as the EM transition rates to be expected in this nucleus. It is hoped that from the analysis of the present He$^3$ induced reactions on C$^{12}$ one
can obtain additional information on the properties of the states of $N^{1h}$ as well as those of the compound nucleus $O^{15}$.

From the experimental point of view, a detailed study of the $He^3$ induced reactions on $C^{12}$ has its own importance. Most of these reactions have higher cross sections when compared with many $He^3$ induced reactions with other targets. Furthermore there are many outgoing groups for the $He^3$ bombardments of $C^{12}$. These groups have energies from a few hundred keV to over 10 MeV.

It is a well-known fact that carbon deposits on a target during an experiment is unavoidable. This makes the carbon contamination correction a difficult task in the study of some $He^3$ induced reactions on other targets. It is hoped that the present measurements of all the $He^3$ induced reactions on $C^{12}$ can provide some help in the study of some other $He^3$ induced reactions.

In addition to the fact that the knowledge of the total cross section of the reaction $N^{1h}(p,n)O^{1h}$ provides some more information in the interpretation of the $He^3$ induced reactions on $C^{12}$, the threshold measurement of this $N^{1h}(p,n)O^{1h}$ reaction has its own interest, namely, the determination of the end point energy of $\beta^+$ spectrum of the transition $O^{1h}(\beta^+, \gamma)N^{1h*}$ (2.311-MeV States) which yields the $\beta^+$ value of this $O^+\rightarrow O^+$ beta transition. (The accurate determination of this $\beta^+$ value is essential in obtaining the precise value of the coupling constant $G_\gamma$ for the vector nuclear beta decay which in turn establishes the exact degree of equality of the coupling constant $G_\gamma$, for the vector nuclear beta decay, and $G_\mu$, for the muon decay. This last
information is essential in the justification of the hypothesis of the conserved-vector-current of Feynman and Gell-Mann in their idea that all of the "weak interactions" proceed by a universal Fermi interaction \(^6,7\).

An energy level diagram appropriate for describing the reactions discussed in the present work is shown in fig. 1. Upon bombarding \(^{12}\)C by \(^3\)He, the outgoing channels consist of proton groups to the various states of \(^{14}\)N, alpha groups to the ground and the first excited states of \(^{11}\)C, neutrons to \(^{14}\)O, and the gamma rays following the decay of the residual nuclei. The levels shown here are from recent compilations \(^8\). The \(J^\pi\) values marked at the sides of the nuclear level diagrams were from the analyses in the present work.
Figure Captions

Fig. 1. Energy level diagram describing the reactions discussed in
the present work. Levels are from ref. 8. The $J^\pi$ values
marked on the side of each nucleus are parameters obtained
from the present work.

Fig. 2. Typical plots of the outgoing particles of $^{12}$C+$^{3}$He reactions:

a. $E_{\text{lab}}$ vs. $\theta_{\text{lab}}$ at $E_{\text{He}^3} = 4.50$ MeV

b. $E_{\text{lab}}$ vs. $E_{\text{bomb}}$ at $\theta_{\text{lab}} = 76^\circ$.

Fig. 3. Charged particle energy spectra. Detector A was an Ortec
solid state detector which had a very thin gold coating on
the face. Detector B was an RCA diffused-junction detector
which had a thicker layer of coating on the face. Spectra
(a) and (b) show the relative positions of proton groups
and the doubly-charged groups from the two detectors taken
under the same experimental conditions. Spectra (c) and
(d) were taken under another similar experimental conditions
except that a 0.0004" Al sheet was in front of detector A
and a 0.0005" Al sheet was in front of detector B. Spectra
(c) and (d) show that the elastic He$^3$ particles were
stopped by the Al sheets. The linearity of the detector
is shown in (a) with particle energies plotted against
the channel numbers.

Fig. 4. Schematic diagram of the apparatus for measuring the gamma-
ray excitation curves and angular distributions. The 2"x2"
NaI was used as monitor in the angular distribution measure-
ments.
Figure 1
Figure 3
Figure 4
II. EXPERIMENTAL METHODS

The $\text{He}^3$ beam of the Rice University 5.5 MeV Van de Graaff accelerator was used for the $\text{He}^3$ induced reactions on $\text{C}^{12}$. For the reaction $\text{N}^{14}(\text{p},\text{n})\text{O}^{14}$ the proton beam of the 12 MeV tandem accelerator was used.

In the measurements of the various outgoing radiations, the different kinds of experimental apparatus were used according to the nature of the radiations. The methods used in the identifications and measurements of these various radiations are described in some detail in the following separate sections.

1. Charged particle detection

1.1 Scattering chamber: All the charged particle measurements were carried out by using the small scattering chamber first constructed by Kashy et al.\textsuperscript{9}), designed for use with self-supporting targets. The chamber consists mainly of two shallow cylinders. The lower remained fixed, while the upper could be rotated with respect to the lower. The target was mounted in the lower cylinder, which also contained the beam defining slits. The two detectors and the slit systems defining the solid angle for scattering into the detectors were mounted in the upper cylinder at $75^\circ$ to its axis of rotation. The angle of scattering was set in terms of the angle $\phi$, indicated by graduations which were made on the top and bottom halves of the chamber. The angle of scattering $\theta$ is then $\arccos(\cos 15^\circ \cos \phi)$. The overall accuracy of the angle of scattering was estimated to be $\pm 0.5^\circ$. The two detectors were mounted at a fixed angle ($\phi_2 - \phi_1 = 90^\circ$). The solid angle used throughout all
the measurements were $4.06 \times 10^{-4}$ Ster. which gave reasonable counting rate and still preserved the good resolution to see all the particle groups. After passing through the target the $\text{He}^3$ ions were collected in the Faraday cup with an electron suppressor of 300 volts applied to a ring in front of the Faraday cup. An additional diffusion pump was added directly to the bottom of the chamber after passing through a liquid nitrogen trap. This pump maintained the chamber at a better vacuum which helped reduce the carbon buildup rate on the target.

1.2 Targets: The methods of preparation of foil targets was the same as described by Kashy et al. The thicknesses of the targets used varied from 15 to 25 $\mu g/cm^2$. The determination of target thickness and reaction cross sections were based on the comparison with the published differential cross sections for the scattering of protons by $\text{C}^{12}$ at an incident proton energy of 3.0 MeV and lab angle of 165°. Since the carbon foils used were extremely thin, the cracking of carbohydrates from the vacuum system on to the foils resulted in a sizeable increase in the target thickness. At the end of each extended run on an excitation curve or angular distribution, a correction for this effect was obtained by taking a number of widely spaced check points of the target thickness. During all of the experiments, the beam was kept off the target between data points.

1.3 Detectors: For $\text{He}^3$ on $\text{C}^{12}$, there are many outgoing particles having energies distributed over a spectrum from a few hundred keV to nearly 10 MeV. In order to obtain all of these groups, a high resolution and high stopping power detector was needed. Two RCA diffused-junction detectors and one Ortec solid state detector were used in the present
measurements. They all have good resolution and high stopping power. From the spectra shown in fig. 3, one can see that all the groups are well resolved and the linearity is good for protons up to 10 MeV.

1.4 Multichannel analyzers: As there were many closely situated and very narrow peaks on the particle spectra, a multichannel analyzer with large numbers of channels was required. A TMC 400-channel analyzer or a Nuclear Data 2-dimensional analyzer in the 511-channel mode, or both, were used in many of the experiments.

1.5 Identification of the various outgoing radiations: For He\(^3\) on C\(^{12}\) the possible reactions involving charged particles as outgoing radiations in the present bombarding energy regions are:

\[
\begin{align*}
\text{C}^{12} + \text{He}^{3} &\rightarrow \text{O}^{15} \rightarrow \text{He}^{3} + \text{C}^{12} \\
&\rightarrow p_0^+ + N_1^{14} \quad \text{(ground state)} \\
&\rightarrow p_1^+ + N_1^{14*} \quad \text{(2.31 MeV state)} \\
&\rightarrow p_2^+ + N_1^{14*} \quad \text{(3.95 MeV state)} \\
&\rightarrow p_3^+ + N_1^{14*} \quad \text{(4.91 MeV state)} \\
&\rightarrow p_4^+ + N_1^{14*} \quad \text{(5.10 MeV state)} \\
&\rightarrow p_5^+ + N_1^{14*} \quad \text{(5.69 MeV state)} \\
&\rightarrow p_6^+ + N_1^{14*} \quad \text{(5.83 MeV state)} \\
&\rightarrow p_7^+ + N_1^{14*} \quad \text{(6.23 MeV state)} \\
&\rightarrow p_8^+ + N_1^{14*} \quad \text{(6.44 MeV state)} \\
&\rightarrow p_{11}^+ + N_1^{14*} \quad \text{(7.03 MeV state)} \\
&\rightarrow \alpha_0^+ + \text{C}^{11} \quad \text{(ground state)} \\
&\rightarrow \alpha_1^+ + \text{C}^{11*} \quad \text{(2.00 MeV state)}
\end{align*}
\]

where the subscripted numbers were assigned to the outgoing particles.
for convenience. We will see later that the proton groups to the
tentatively assigned\textsuperscript{8}) states of $^1\text{n}$ at $E_x = 6.05$ MeV ($p_7$) and
$E_x = 6.70$ MeV ($p_{10}$) were not observable in all the present experiments.
The Q values given here were from the known energy level diagrams\textsuperscript{8}).
To identify all the outgoing particles unambiguously one can first make
a kinematical calculation to predict the expected laboratory energies
of these particles at chosen laboratory angles and bombarding energies
for comparison with the spectrum obtained under the same conditions.
In the actual identification, the expected laboratory energies of the
various outgoing particles were computed at many laboratory angles and
bombarding energies. The plots of $E_{\text{lab}}$ vs. $\theta_{\text{lab}}$ for a number of
bombarding energies were made for all the outgoing particles. Also
plots of $E_{\text{lab}}$ vs. $E_{\text{bomb}}$ were made for a number of laboratory angles.
These curves are shown in figs. 2a and 2b. With these two kinds of
plots as reference one can always make a quick check of the spectrum
whenever there is a doubt while taking an angular distribution or an
excitation curve. Figure 3 shows some typical spectra with the identifi-
cation of the various particle groups.

1.6 Methods of taking data: Since the variation of laboratory
energies of the outgoing He\textsuperscript{3} and $\alpha$ particles are different from those
of protons (see fig. 2), there are always regions where the overlapping
of the doubly charged particles and protons can occur. In order to
obtain a complete measurement in these overlapping regions, two
detectors having different thicknesses of stopping material on the
detector surfaces were used to make two successive measurements at the
same angle and energy. From the fact that doubly charged particles
lose more energy than protons of nearly the same energy when passing
though stopping material, the α and He\textsuperscript{3} groups will shift more than proton
groups adjacent to them in a spectrum. One can compare the spectra
obtained with different thicknesses of stopping material and make a full
identification of the groups. A typical pair of spectra measured in
this way are shown in figs. 3a and 3b. The fact that two detectors
could be used at the same time greatly simplified the experiment.

For data at forward angles thin Al foils were used to stop the
elastic He\textsuperscript{3} group. Typical spectra taken in this way are shown in
figs. 3c and 3d.

At the beginning of each experiment, an energy calibration was
made by measuring the C\textsuperscript{13}(p,n)N\textsuperscript{13} threshold. All the energy scales
were calibrated using $E_{TH} = 3.235 \text{ MeV}$\textsuperscript{12}.

2. Neutron detection\textsuperscript{*}

It can be seen from the Q value that only the ground state neutron
group from the reaction C\textsuperscript{12}(He\textsuperscript{3},n)O\textsuperscript{14} can be observed in the present
bombarding energy region. The neutrons were detected by a B\textsuperscript{10} enriched
BF\textsubscript{3} proportional counter, about 2.6 cms in diameter and 15 cms in
effective length, embedded in a paraffin cylinder 15 cms in diameter

\textsuperscript{*} The reaction C\textsuperscript{12}(He\textsuperscript{3},n)O\textsuperscript{14} was first investigated by Din, Kuan, and
Bonner\textsuperscript{13,14}). The outline of the experiment is described here to
complete the discussion of the C\textsuperscript{12}+He\textsuperscript{3} reactions in the present
energy region. A more detailed description of the experiment is in
process of publication. The kind permission of Mr. Din to include
this part is appreciated.
and 12.2 cms long. The distance from the front surface of the paraffin cylinder to the target was about 28 cms for 0° excitation curve, 14 cms for 90° excitation curve, and 42.5 cms for the angular distribution measurements.

The carbon target for the excitation curves was made by cracking spectroscopically pure ethane gas onto a .01 inch tungsten backing. It was about 40 keV thick for 3 MeV He³ beam. The target for the angular distributions was made in the same way using a .024" Ta backing. The plane of the target was at 45° to the beam in the angular distribution measurements.

An estimate of the C¹²(He³,n)O¹⁴ reaction cross section was based on the comparison with the known cross sections of the C¹²(d,n)N¹³ reaction¹⁵). The same carbon target and neutron detector set-up was used for the two reactions C¹²(He³,n)O¹⁴ and C¹²(d,n)N¹³. The bombarding energies were set to give nearly the same outgoing neutron energy to avoid the correction due to the difference in response of the detector to neutrons of different energies. The actual settings were E_d = 1.8 MeV and E_He³ = 2.9 MeV. A correction for the energy variations of counter efficiency was applied to the data using the calibrated efficiency curve of a neutron counter consisting of a neutron detector embedded in a 5-inch sphere of polyethylene¹⁶). Because the volume of the 5-inch polyethylene sphere has about the same as that of the paraffin cylinder used in the present experiment, the two counters would be expected to have approximately the same efficiency curve.

3. Gamma-ray detection

The present part of the investigation on the gamma rays from the
\( \text{He}^3 \)-induced reactions on \( \text{C}^{12} \) is essentially an extension with special attention to the 6.43-MeV gamma ray of the author's previous work\(^{17}\). In that work, it was uncertain which one of the 6.43- and 6.23-MeV gamma rays gives rise to the strong resonance at 3 MeV \( \text{He}^3 \) energy. The excitation curves and angular distributions were obtained with a single channel analyzer. The window setting of the analyzer was based solely on the comparison of a differential bias curve from a single channel analyzer with the spectrum from a 256-channel analyzer, so that it was not possible to observe and correct for small gain variations of the photomultiplier due to the change in the counter position during angular distribution measurements. The improved measurements of the present work are described in the following paragraphs.

3.1 Experimental arrangement: A 1"x1" NaI scintillator was used for angular distribution measurements, and a 2"x2" NaI for the excitation curves. A \( \mu \)-metal shield was used on the photomultiplier to reduce gain variations. A schematic diagram of the experimental arrangement is shown in fig. 4. The positioning of the 1"x1" detector is shown as it was for the angular distribution measurements. For the excitation-curve measurements, the 2"x2" detector was placed as close as possible to the target.

The pulse from the output of the single channel pulse-height analyzer of the Hamner amplifier-analyzer was used to gate the 256-channel analyzer as shown in fig. 4. The data for the angular distributions were taken from the print-out of the spectrum from the 256-channel analyzer. The coincidence from the single channel in integral mode was used to prevent the 256-channel analyzer from processing low energy pulses. The excitation curve data were taken with the single
channel analyzer in differential mode. The coincidence was used in setting the upper and lower biases by inspection of the spectrum shown by the 256-channel analyzer to be in the window of the single channel analyzer.

3.2 **Measurements of the excitation curve of the 6.44 MeV gamma rays:** The fact that it was the 6.44 MeV gamma rays which contribute the strong resonance at 3 MeV is shown clearly from a comparison of spectra taken below, on, and above the resonance, at $E_{\text{He}} = 2.62; 2.99; 3.46$ MeV shown in fig. 5. The spectra obtained by subtracting the spectra away from resonance from the spectrum on the resonance show clearly the 6.44 MeV gamma rays. The gamma-ray energy scale in fig. 5 was from the 4.43 MeV gamma-ray source of PuBe.

For each excitation curve measurement, the window could be set very accurately using the 256-channel analyzer in coincidence with the single channel analyzer. Then, the excitation curve could be obtained from the readings of the scaler on the output of the single channel analyzer. The spectrum for each data point was checked to watch for possible gain shift. Since good magnetic shielding was used and the counter was at fixed position, there was no gain shift in the excitation curve measurements.

The window setting for the 6.44 MeV gamma-ray excitation-curve measurement was from the first escape peak to the end of photo peak, as seen in fig. 5.

3.3 **Measurements of the 6.44 MeV gamma-ray angular distribution:** To show that the angular distribution measured on the resonance was really from the 6.44 MeV gamma rays, the spectra obtained at $\theta = 30^\circ$ and
Figure Captions

Fig. 5. Gamma-ray spectra from $^{12}\text{C}^{3}\text{He}$ reactions taken below the 2.99 MeV resonance (2.62 MeV), on the resonance (2.99 MeV), and above the resonance (3.46 MeV). The differences in the spectra taken on the resonance and off the resonance show clearly the contribution of the 6.44 MeV gamma ray to the resonance.

Fig. 6. Gamma-ray spectra at $30^\circ$ and $90^\circ$ from the measurement of the angular distribution at the 2.99 MeV resonance. The difference between these two spectra shows clearly that the 6.44 MeV gamma ray is responsible for this resonance.

Fig. 7. A typical 2.31 MeV decay gamma-ray spectrum from $^{14}\text{N}^{14}(p,n)^{14}\text{O}$, using a 4"D. x 6"L. Pilot B detector. The window setting includes mainly the Compton edge of the 2.31 MeV gamma ray.

Fig. 8. A typical 0.114 decay from $^{14}\text{N}^{14}(p,n)^{14}\text{O}$ (at $E_p = 10$ MeV). The open circles are backgrounds taken before making the measurements.
Figure 5
90° are shown in fig. 6. The spectrum obtained by subtracting the 90°
spectrum from the 30° one shows clearly that the 6.4MeV gamma ray is
the cause of the difference in the yield between 90° and 30°.

In actually taking data, the single channel scaler reading and
the multi-channel spectrum were both recorded for each data point. As there
were still small gain shifts and the single channel scaler data were not
good enough for analysis, the final data were obtained from the analysis
of the spectrum taken at each angle. All the spectra were plotted out.
The shift of gain could easily be observed from the shifts of peak
positions of the many peaks in the spectrum. Then the area of the
spectrum above the second escape peak of the 6.4 MeV gamma rays was
taken (see fig. 6). The measurements were repeated four times with two
different targets. There was good agreement between the data of the
four runs.

Corrections for the attenuation loss from the target backing and
the wall of the target chamber, as well as corrections for carbon build-
up, were applied to the final data. The maximum build-up correction was
about 9% for the last data point compared with the first data point. The
maximum attenuation loss was about 10% at the backward angle.

4. Total neutron cross section measurements

4.1 Targets: The carbon target for the C<sup>12</sup>(He<sup>3</sup>,n)C<sup>14</sup> total cross
section measurement was made by cracking CH<sub>4</sub> gas on to a .01" tungsten
blank. Its thickness was about 20 μg/cm<sup>2</sup>, obtained by comparing the
yields of neutrons and gamma rays from C<sup>12</sup>+He<sup>3</sup> reactions with the yields
from a thin self-supporting C<sup>12</sup> target. The thickness of the latter was
measured in terms of well-known elastic proton cross sections using the
method described in the section on charged particle detection.

The two nitrogen targets used for the $^N_{14}(p,n)_0^{14}$ total cross-section measurement were made by heating a .02 inch Ta blank in natural nitrogen gas. Their thicknesses were determined by measuring the width of the 2.2 keV resonance of $^N_{15}(p,\alpha_1\gamma)C^{12*}$ (4.43 MeV state) at $E_p = 0.898$ MeV, using a 1"x1" NaI(Tl) crystal to detect the 4.43 MeV gamma rays. The targets were about 40 keV and 75 keV thick for 0.9 MeV protons.

4.2 Detector: In order to avoid the neutron activation in the NaI crystal (this is especially serious when using the tandem accelerator with proton energies higher than 8 MeV) and at the same time to obtain a reasonably high efficiency, a 4"x4.6"x6.6". Pilot B scintillator, mounted on a DuMont 6363 photomultiplier, was used for detecting the 2.31 MeV decay gamma rays from both the $C^{12}(He^3,n)_0^{14}$ and $N^{14}(p,n)_0^{14}$ reactions.

4.3 Multi-channel analyzer: The multi-channel scaler operation of a TMC 400 channel pulse height analyzer was used to count the decay gamma rays. In this mode of operation all the pulses within a preset window defined by a single channel analyzer in coincidence with the 400-channel analyzer, are recorded in one channel for a preset time (1 sec per channel was used). At the end of the preset time, the instrument advances automatically to the next channel and records in that channel for the same preset time. To avoid the 0.511 MeV annihilation gamma-ray pulses and other low energy pulses, a window was set to count only the Compton edge of the 2.31 MeV gamma rays. A coincidence mode similar to the one described in the section on gamma-ray detection was employed to make window setting easier. At the beginning of each experiment or
"set run" the spectrum of the window setting was checked. Figure 7 shows a pulse-height spectrum for the 2.31 MeV decay gamma rays from $^{114}$O.

4.4 Methods of taking data: The methods of taking data are based on the following relations:

Let $M = \text{number of nuclei activated per sec by the beam}$,

$$ Q = \frac{Q}{\varepsilon T} A \sigma $$

for a constant beam current,

where $Q = \text{total charge collected for a data point}$,

$T = \text{total time beam is on the target}$,

$A = \text{number of target nuclei}$,

$\sigma = \text{cross section of the reaction}$,

$\varepsilon = \text{charge of the incident particle}$.

And let

- $N = N(t) = \text{number of nuclei present at time } t$
- $dN = dN(t) = \text{increase in the number of nuclei during } dt$
- $\lambda = \text{decay constant}$.

Then $dN = Md\tau - \lambda N d\tau$.

Keeping $M$ constant (i.e. keeping beam current constant) and integrating from $t = 0$ to $T$,

since $N = 0$ when $t = 0$, we have

$$ N_T = N(\tau) = M \frac{\lambda}{\lambda - \varepsilon (1 - e^{-\lambda T})}. $$

Since

$$ M = \frac{Q}{\varepsilon T} A \sigma, $$

$$ \sigma = \frac{\varepsilon N_T A T}{Q A (1 - e^{-\lambda T})}. $$

From this cross-section expression it can be seen that there are two methods of taking data. The first method is to bombard the target with a constant beam current for a definite time $T$ and count the decay
immediately after the beam is off the target. If the counts are plotted against time on semi-log graph paper, linear extrapolation to zero time yields a number proportional to \( N_T \) with a constant factor of proportionality. As the bombarding time \( T \) is kept the same for all data points, we have, from the above expression for \( \sigma \):

\[
\sigma \propto \frac{\bar{N}}{Q}
\]

where \( \bar{N} = \text{counts extrapolated to } t = 0 \)

\( Q = \text{total charge collected in each bombardment.} \)

The second method is to keep the total charge \( Q \) collected constant (i.e. to turn off the beam when a definite amount of charge is collected). Then,

\[
\sigma \propto \frac{\bar{N} T}{1 - e^{-\lambda T}}
\]

For experimental convenience, the first method was used for the \( C^{12}(\text{He}^{3},n)O^{14} \) total cross-section measurement and the second method for the \( N^{11}(p,n)O^{14} \) total cross-section measurement. Also, in the actual taking of data, the 400 channel analyzer was started 5 seconds after the beam was turned off the target in order to allow a time to turn down the accelerator to reduce the room background. The sum of the first 30 seconds was used for \( \bar{N} \). For each bombardment the decay was measured up to 900 seconds or about 15 half lives, and the background was recorded before starting a new point.

Figure 8 shows one of the decay curves. It shows a half life of 73 \( \pm \) 2 seconds with a typical background. The background was less than one-half of a per cent of the end point counts for most of the data, except for the points near thresholds and for the \( N^{11}(p,n)O^{14} \) reaction from 10 to 12 MeV, where the background was about 3%. The background
correction was made for the final results shown in figs. 25, 26, but was
not made for the yields near thresholds, fig. 27.

The effect of the Ta backing on the experimental $^\text{N}^{1\text{l}}(p,n)^{0\text{l}}$ yield
has also been corrected from a measurement of the yield of a Ta foil which
was not heated in nitrogen gas. The yield of the blank foil rises
smoothly from less than 1% of the yield from the nitrogen target at 7
MeV to about 30% at 12 MeV. The difference between yields from the
target heated in the nitrogen gas and from the blank Ta foil is presumed
to be the yield from the reaction. The yields corrected for background
are shown in fig. 26 as the final results. The yield from the blank Ta
foil alone is also shown in fig. 26.

The fluctuation of the beam current can introduce errors into the
results. The beam current was kept constant for each bombardment through-
out the experiment. No adjustment of the accelerator controls was made
after about 5 seconds from the beginning of the bombardment. The beam
was observed to be quite steady. When unsteady beam conditions developed,
the point was stopped, the activity was allowed to decay, and the point started
over again. The final data was the average of at least 2 runs, and in most
cases 3 runs.

4.5 Estimate of the absolute cross sections: The absolute total
neutron cross sections of $^{12}\text{(He}^3,n)^{0\text{l}}$ was obtained from a neutron
angular distribution. The absolute cross section of $^{12}\text{(He}^3,n)^{0\text{l}}$ was
obtained by comparing with the known cross section of $^{12}\text{(d,n)}^{1\text{N}}$ as
described in the section on neutron detection.

To determine the absolute cross section of $^{1\text{l}}(p,n)^{0\text{l}}$ the decay
gamma rays were counted by a 1"x1" NaI scintillator placed at a known
distance from the target. By using the efficiency curve of NaI crystal the absolute yield of gamma rays were obtained. From these and the measured target thickness, the cross sections were calculated from the expression of cross section on page 15. The uncertainty in the determination is about 50%.

4.6 Determination of threshold energies: The calibration of energy scales for the $^{12}\text{C}(\text{He}^3,n)$ and $^{14}\text{N}(p,n)$ threshold measurements were made against the $^{13}\text{C}(p,n)$ threshold. The threshold energy of 3.2352 MeV for this reaction was used\textsuperscript{12}. The results of these calibration "runs" are shown in fig. 9.
Figure Captions

Fig. 9. $^{13}\text{C}^{(p,n)^{13}}$ threshold measurements for the calibrations of the energy defining magnets of the 5.5 MeV Van de Graaff and the 12 MeV tandem accelerator. The threshold energies for the $^{12}\text{C}^{(\text{He}^3,n)}$ and $^{11}\text{N}^{(p,n)}$ reactions were based on these calibration measurements.

Fig. 10. Differential elastic C.M. scattering cross sections of $^{12}\text{C}^{(\text{He}^3,\text{He}^3)}^{12}$ at C.M. angles 84.5°, 90°, 122.3°, 154.5°, and 164.5°. The lines are theoretical fits (see table 1) and Rutherford cross sections.

Fig. 11. Differential cross sections at laboratory angles 76° and 159.4°, and angular distributions at 2.49, 2.88, 2.99, 3.50, 4.20, and 4.88 MeV of the reaction $^{12}\text{C}^{(\text{He}^3,p)}N^{11}$. The solid lines were drawn through the data points. The arrows marked the positions where angular distributions were measured.

Fig. 12. Differential cross sections at laboratory angles 76° and 159.4°, and angular distributions at 2.49, 2.88, 2.99, 3.15, 3.50, 4.20, and 4.88 MeV of the reaction $^{12}\text{C}^{(\text{He}^3,p_1)}N^{11}$ (2.31 MeV state). The solid lines were drawn through the data points. The arrows marked the positions where angular distributions were measured.
Figure 10
Figure 11
$^{12}\text{C}(^{3}\text{He},p){}^{14}\text{N}^{*}(2.31\text{ MeV }\text{STATE})$

$\sigma(\theta)_{\text{C.M.}}$ (MB/Steradian)

\begin{align*}
\text{Energy} & \quad \sigma(\theta)_{\text{C.M.}} \\
2.49\text{ MeV} & \quad \text{Data Points} \\
2.88\text{ MeV} & \quad \text{Data Points} \\
2.99\text{ MeV} & \quad \text{Data Points} \\
3.15\text{ MeV} & \quad \text{Data Points} \\
4.20\text{ MeV} & \quad \text{Data Points} \\
4.88\text{ MeV} & \quad \text{Data Points} \\
\end{align*}

$\theta(\text{Lab}) = 76^\circ$

$\theta(\text{Lab}) = 159.4^\circ$

Figure 12
III. EXPERIMENTAL RESULTS

The results are described in some detail in the following sections according to the nature of radiations. Excitation curves and angular distributions were obtained for all of the outgoing charged particles. The statistical variations of each data point varied from 15% to 2% depending on the cross sections of the various outgoing radiations. But most of the data have been repeated 2 to 6 times with good agreement. Typical statistical errors for the final data obtained after averaging are shown in the results.

1. \(^{12}\text{C}(\text{He}^3,\text{He}^3)^{12}\text{C}\)

The elastic scattering results are presented in fig. 10. The curves in the figure are theoretical calculations. They will be discussed later. Since the original interest was in the 3 MeV region, measurements in this energy region were made at many angles:

\[ \Theta_{\text{c.m.}} = 84.5^0, 90.0^0, 122.3^0, 154.5^0, 164.5^0 \].

However, at two angles, \( \Theta_{\text{c.m.}} = 90.0^0 \) and \( 164.5^0 \), the measurements were extended from 1.8 to 5.4 MeV. Measurements at \( \Theta_{\text{c.m.}} = 114.5^0 \) near 4.2 MeV region were also taken (not shown in the figure).

Besides the pronounced resonance structure in the 3 MeV region which appeared in all the measured angles, the indication of resonance structures from 4.5 to 5.2 MeV and in the 4.2 MeV region can also be seen from data taken at \( \Theta_{\text{c.m.}} = 164.5^0 \) and \( 114.5^0 \). In general, one would not expect the resonances in the elastic scattering of \( \text{He}^3 \) from \( ^{12}\text{C} \) to be very strong because there are many open channels in this energy region.
This reaction has been previously studied by Forsyth and Manl\textsuperscript{18}) using a solid state detector. But their detector was not thick enough to stop all the particle groups occurring in the reactions, so that there was background from groups which could not be fully stopped. Their cross sections were determined by normalization to the Rutherford scattering at the forward angle. It was believed that the present measurements have better accuracy. The present cross sections were determined from comparison with the well known elastic scattering as mentioned before. A correction for the existence of residual singly ionized He\textsuperscript{+} ions in the beam after passing through the target foil was applied. Better detectors were used which could stop all the particles formed in the reactions. The data in the region where overlapping of groups were expected were also obtained using the method (comparing spectra from two detectors with different thicknesses of stopping material on the face) described before. Therefore, only the present results were used in the theoretical analysis.

2. C\textsuperscript{12}(He\textsuperscript{3},p)He\textsuperscript{14} with proton groups corresponding to the formation of the He\textsuperscript{14} ground state and excited states at 2.31, 3.95, 4.91, 5.10 5.69, 5.83, 6.23, 6.64, and 7.03 MeV (designated by p\textsubscript{0}, p\textsubscript{1}, p\textsubscript{2}, p\textsubscript{3}, p\textsubscript{4}, p\textsubscript{5}, p\textsubscript{6}, p\textsubscript{8}, p\textsubscript{9}, and p\textsubscript{11}, respectively)

Bromley et al.\textsuperscript{19}) have measured the differential cross sections and some angular distributions of the p\textsubscript{0}, p\textsubscript{1}, p\textsubscript{2} groups from 1.0 to 3.0 MeV. Johnston et al.\textsuperscript{20}) have measured differential cross sections at 6 lab angles, $\Theta_{\text{lab}} = 7^0, 30^0, 60^0, 90^0, 120^0, 150^0$, of p\textsubscript{0}, p\textsubscript{1}, p\textsubscript{2}, (except that p\textsubscript{2} was not measured at 90\textdegree) from 2.0 to 5.0 MeV. They
have also obtained angular distributions at 2.0 and 4.5 MeV of these $P_0, P_1, P_2$ groups. At higher energies, Hinds and Middleton\textsuperscript{21} have reported the differential cross sections at $\theta_{\text{lab}} = 10^\circ$ and angular distributions at 5.98, 8.83, 9.37, and 10.14 MeV of $P_0, P_1, P_2, P_3, P_4, P_5,$ and $P_6$ groups.

In the present work, differential cross sections at $\theta_{\text{lab}} = 76^\circ$ and $159.4^\circ$ and angular distributions at 2.49, 2.88, 2.99, 3.50, 4.20, and 4.88 MeV were measured for most of the groups from $P_0$ to $P_{11}$. Differential cross sections at $\theta_{\text{lab}} = 60^\circ$ and $90^\circ$ for $P_0$ and $P_1$ were also measured (not shown in the following figures). The results agree with the results of Johnston et al.\textsuperscript{20}, except that the absolute cross sections of the present results are about 10% higher than theirs. Within the uncertainties quoted by Johnston et al. (20%) and in the present work (10%), the agreements in general are good.

The results on $P_3, P_4, P_5, P_6, P_8, P_9$, and $P_{11}$ in the present energy regions (1.8 - 5.4 MeV) have no previous report for comparison.

Summarizing the above information, one can say, approximately, that the experimental information of $P_0, P_1, P_2$ were obtained from 1.0 to 10.23 MeV, that of $P_3, P_4, P_5, P_6$ from 1.8 to 10.23 MeV, and that of $P_8, P_9, P_{11}$ from 1.8 to 5.4 MeV.

As can be seen by glancing at all these results, one general feature is that pronounced and broad resonance structures appear in most of the groups, extending over the whole energy range. But many resonance positions vary from angle to angle and group to group, so that one cannot give an immediate assignment of the resonance positions.

More detailed descriptions of the results on the proton groups
individually are given below.

2.1 \( ^{12}\text{C}(\text{He}^3, \alpha)^{11}\text{H} \) (ground state): Differential cross sections at \( \theta_{\text{lab}} = 76^\circ \) and 159.4\(^\circ \) and angular distributions at 2.49, 2.88, 2.99, 3.50, 4.20, and 4.88 are shown in fig. 11. The results are in good agreement with Johnston's work\(^{20} \) in the 2 to 5 MeV region. The angular distribution at 4.88 is quite like that at 5.98 MeV in the work of Hinds and Middleton\(^{21} \).

The general features of the angular distributions are that there is no consistent peaking forward, and that the shape does not vary very much from resonance to resonance.

2.2 \( ^{12}\text{C}(\text{He}^3, \alpha)^{11}\text{H} \) (2.31 MeV state): Differential cross sections at \( \theta_{\text{lab}} = 76^\circ \) and 159.4\(^\circ \) and angular distributions at 2.49, 2.88, 2.99, 3.15, 3.50, 4.20, and 4.88 MeV are shown in fig. 12. The results agree very well with Johnston's work\(^{20} \). The angular distribution at 4.88 MeV is quite similar to that at 5.98 MeV obtained by Hinds and Middleton\(^{21} \) except that there is more peaking forward at 5.98 MeV.

The general features of the angular distributions are the rapid variation in the 2 to 3 MeV regions and the consistent peaking forward above 4.8 MeV. (Fig. 12 and ref. 21).

The angular distribution at 2.99 MeV was measured very carefully 3 to 4 times for the purpose of making an analysis which, with the analyses of the \( p_9, \gamma_{6.49} \), and elastic \( \text{He}^3 \) data, would aid in making assignments at this energy.

2.3 \( ^{12}\text{C}(\text{He}^3, \alpha)^{11}\text{H} \) (3.94 MeV state): Differential cross sections at \( \theta_{\text{lab}} = 76^\circ \) and 159.4\(^\circ \) and angular distributions at 2.49, 2.88, 2.99,
3.50, 4.20, and 4.88 MeV are shown in fig. 13.

The results agree very well with Johnston's work\textsuperscript{20).} The fact that Johnston did not get the differential cross sections at $\theta_{\text{lab}} = 90^0$ and $60^0$ is probably due to the overlapping of $p_2$ and $\alpha_0$ in this region. In the present work the results in the overlapping region were obtained by using the methods previously described.

The angular distributions show 3 general types of shape. Those of
the first type, at 2.49 and 4.20 MeV, are probably due to the effects of
resonances which can be seen at 2.40 and 4.40 MeV in the 159.40 excitation
curve. Those of the second type, at 2.88, 2.99, and 3.50 MeV, have
similar shapes, probably associated with the fact that the excitation
curves show no large variations in this energy region. A third type,
at 4.88 MeV has a shape similar to the angular distribution at 5.98 MeV
obtained by Hinds and Middleton\textsuperscript{21).}

$^{2}\text{H}$ C$^{12}$$(\text{He}^3, p_3)\text{H}^{11}$ (4.91 MeV state): Differential cross sections
at $\theta_{\text{lab}} = 76^0$ and 159.50 and angular distributions at 2.49, 2.88, 2.99,
3.50, 4.20, and 4.88 MeV are shown in fig. 14.

Two pronounced broad resonances appear in the 159.40 excitation
curve centered at 3.75 and 4.75 MeV. The angular distributions at
2.49, 2.88, 2.99, and 3.50 MeV show larger cross sections at backward
angles, and the two angular distributions at 4.20 and 4.88 MeV show
resonance structure. The 4.88 MeV angular distribution has a shape
similar to the one at 5.98 MeV obtained by Hinds and Middleton\textsuperscript{21) up to}
$\theta_{\text{c.m.}} = 120^0$. Unfortunately Hinds and Middleton show no data at
backward angles.
Figure Captions

Fig. 13. Differential cross sections at laboratory angles 76° and 159.4°, and angular distributions at 2.49, 2.88, 2.99, 3.50, 4.20, and 4.88 MeV of the reaction $^{12}$C($^3$He,$^2$P$_2$)$^{14}$N$_{14}^*$ (3.91 MeV state). The solid lines were drawn through the data points. The arrows marked the positions where angular distributions were measured.

Fig. 14. Differential cross sections at laboratory angles 76° and 159.4°, and angular distributions at 2.49, 2.88, 2.99, 3.50, 4.20, and 4.88 MeV of the reaction $^{12}$C($^3$He,$^3$P$_3$)$^{14}$N$_{14}^*$ (4.91 MeV state). The solid lines were drawn through the data points. The arrows marked the positions where angular distributions were measured.

Fig. 15. Differential cross sections at laboratory angles 76° and 159.4°, and angular distributions at 2.49, 2.88, 2.99, 3.50, 4.20, and 4.88 MeV of the reaction $^{12}$C($^3$He,$^4$P$_4$)$^{14}$N$_{14}^*$ (5.10 MeV state). The solid lines were drawn through the data points. The arrows marked the positions where angular distributions were measured.

Fig. 16. Differential cross sections at laboratory angles 76° and 159.4°, and angular distributions at 2.49, 2.88, 2.99, 3.50, 4.20, and 4.88 MeV of the reaction $^{12}$C($^3$He,$^5$P$_5$)$^{14}$N$_{14}^*$ (5.69 MeV state). The solid lines were drawn through the data points. The arrows marked the positions where angular distributions were measured.
$C^{12}(He^{3},p_{2})N^{4*}(3.945\text{ MeV STATE})$

\[\sigma(\theta)_{\text{C.M.}} \text{ (MB/STERADIAN)}\]

\[\sigma(\theta)_{\text{LAB}} \text{ (MB/STERADIAN)}\]

$\theta(\text{Lab}) = 76^\circ$

$\theta(\text{Lab}) = 159.4^\circ$

Figure 13
\[ C^{12}(\text{He}^3, p_3)N^{14*}(4.91 \text{ MeV STATE}) \]

![Graph showing scattering angles and energies](image)

**Figure 1h**
Figure 16

C^{12}(He^{3},p_{5})N^{14}{^*}(5.69\,\text{MeV\,STATE})

\begin{array}{ccc}
\text{C.M. \text{ANGLE (DEGREES)}} \\
\text{2.49 MeV} & \text{2.88 MeV} & \text{2.99 MeV} \\
\text{3.50 MeV} & \text{4.20 MeV} & \text{4.88 MeV} \\
\end{array}

\sigma(\theta)_{\text{C.M.}} \text{ (MB/STERADIAN)}

\begin{array}{c}
\theta(\text{Lab}) = 76^\circ \\
\theta(\text{Lab}) = 159.4^\circ \\
\end{array}

\sigma(\theta)_{\text{LAB}} \text{ (MB/STERADIAN)}

\text{HELIUM - 3 ENERGY (MEV)}

\text{2.5} \quad 3.0 \quad 3.3 \quad 4.0 \quad 4.3 \quad 5.0 \quad 5.5
2.5 $^4\text{He}^3, p_d \rightarrow ^{14}\text{N}^{1h}$ (5.10 MeV state): Differential cross sections at $\theta_{\text{lab}} = 76^\circ$ and 159.4$^\circ$ and angular distributions at 2.49, 2.88, 2.99, 3.50, 4.20, and 4.88 MeV are shown in fig. 15.

In this proton channel, the excitation curves at $\theta_{\text{lab}} = 76^\circ$ and 159.4$^\circ$ both show pronounced resonance structure, but there is little similarity between them. Notice the small resonance at 3 MeV in the $\theta_{\text{lab}} = 76^\circ$ excitation curve. The small resonance at 4.30 MeV in the 159.4$^\circ$ excitation curve has been repeated 5 times to prove its existence, with good agreement. Notice that this small resonance does not appear at the same position as the one shown in 159.4$^\circ$ excitation curve of $p_1$ group which also have been reported by Johnston et al.\textsuperscript{20} and was used by them to predict a state in $0^{15}$. The resonance appeared in $p_1$ data at 4.35 MeV.

The angular distributions vary from energy to energy above 3 MeV. This is probably due to the presence of many resonances which show in the excitation curves. The angular distributions show no consistent forward peaking, but, rather, backward peaking and structure.

The angular distribution at 4.88 MeV has a shape not quite similar to the 5.98 MeV curve of the Hinds and Middleton\textsuperscript{21}.

2.6 $^\text{12}\text{C}^3\text{He}, p_3 \rightarrow ^{14}\text{N}^{1h*}$ (5.69 MeV state): Differential cross sections at $\theta_{\text{lab}} = 76^\circ$ and 159.4$^\circ$ and angular distributions at 2.49, 2.88, 2.99, 3.50, 4.20, and 4.88 MeV are shown in fig. 16.

In addition to the two broad resonance structures extending from 2.3 to 3.8 MeV and from 4.5 to 5.4 MeV which on both excitation curves at $\theta_{\text{lab}} = 76^\circ$ and 159.4$^\circ$, there are narrower resonances at 2.5 MeV
on both curves, at 3.0 MeV on the 159.4° curve, and at 4.2 MeV on the 76° curve. The 4.2 MeV resonance can also be seen on the 100.2° excitation curve (not shown in the figure). Data in this 4.0 to 4.5 MeV region were repeated 4 times to prove the real shape of the excitation curves, with good agreement. The width of the 3 MeV resonance at 159.4° agrees with that of p( see later results on p).

The angular distributions measured for this group (p) show wide variations. They are isotropic at 2.49 MeV, peak backward at 2.88, 2.99, and 3.50 MeV, peak at θ_c.m. = 105° at 4.2 MeV, and peak forward at 4.88 MeV. The angular distribution at 4.88 MeV is similar to the one at 5.98 MeV from θ_c.m. = 0° to 80° of Hinds and Middleton.²¹

2.7 C^{12}(Ne^{3},p_{6})^{14}N (5.83 MeV state): Differential cross sections at θ_{lab} = 76° and 159.4° from 2.9 to 5.4 MeV, at θ_{lab} = 100.2° from 4.0 to 4.5 MeV and angular distributions at 2.99, 3.50, 4.20, and 4.88 are shown in fig. 17.

The yields are low below 4.0 MeV in the excitation curves and start rising from 4.2 MeV resonance. The 4.2 MeV resonance appearing at θ_{lab} = 76° has the same position and width as it does in the excitation curve of p. The yields at 159.4° of these two groups are also similar. The lab width of the 76°, 4.2 MeV, resonance is about 80 ± 15 keV from the p and p_data.

The angular distributions vary from energy to energy. It seems that the 4.2 MeV angular distribution is mainly due to the 4.2 MeV resonance with some degree of interference with neighboring resonances. The 4.88 MeV angular distribution is similar in shape to the one at 5.98 MeV in the work of Hinds and Middleton, but the cross sections
Figure Captions

Fig. 17. Differential cross sections at laboratory angles 76°, 100.2°, and 159.4°, and angular distributions at 2.99, 3.50, 4.20, and 4.88 MeV of the reaction \( ^{12}\text{C}(\text{He}^3,p\gamma)^{11}\text{H}^* \) (5.83 MeV state). The solid lines were drawn through the data points. The arrows marked the positions where angular distributions were measured.

Fig. 18. Differential cross sections at laboratory angles 76°, 109.3°, 146.6°, and 159.4°, and angular distributions at 2.88, 2.99, 3.50, 4.20, and 4.88 MeV of the reaction \( ^{12}\text{C}(\text{He}^3,p\gamma)^{11}\text{H}^* \) (6.23 MeV state). The solid lines were drawn through the data points. The arrows marked the positions where angular distributions were measured.

Fig. 19. Differential cross sections at laboratory angles 76°, 109.3°, 146.6°, and 159.4°, and angular distributions at 2.99, 4.20, and 4.88 MeV of the reaction \( ^{12}\text{C}(\text{He}^3,p\gamma)^{11}\text{H}^* \) (6.44 MeV state). The solid lines were drawn through the data points for all the curves except the 2.99 MeV angular distribution. The solid lines for the 2.99 MeV angular distribution was the theoretical fit (case 1 of table 3). The arrows marked the positions where angular distributions were measured.

Fig. 20. Differential cross sections at laboratory angles 76°, 109.3°, and 146.6°, and angular distributions at 4.20 and 4.88 MeV of the reaction \( ^{12}\text{C}(\text{He}^3,p\gamma)^{11}\text{H}^* \) (7.03 MeV state). The solid lines were drawn through the data points. The arrows marked the positions where angular distributions were measured.
Figure 17
Figure 19
Figure 20
are about \( n \) times higher at 4.88 MeV.

\[ 2.8 \quad C^{12}(He^3, p_9) N^{1h} \quad (6.23 \text{ MeV state}) \quad \text{Differential cross sections} \]

at \( \Theta_{\text{lab}} = 76^\circ \) and 159.5\(^\circ\) from 2.3 to 5.1 MeV and some results at

\( \Theta_{\text{lab}} = 109.3^\circ \) and \( 146.6^\circ \) and angular distributions at 2.88, 2.99, 3.50, 
4.20, and 4.88 are given in fig. 18.

The yield curves have no large variation with energy except for a relatively narrow resonance appearing at 4.35 MeV in the backward angle data. The yields at backward angles rise above 5 MeV.

The angular distributions have consistent forward peaking for all energies.

\[ 2.9 \quad C^{12}(He^3, p_9) N^{1h} \quad (6.44 \text{ MeV state}) \quad \text{Differential cross sections} \]

at \( \Theta_{\text{lab}} = 76^\circ, 109.3^\circ, 146.6^\circ, 159.4^\circ, \) and angular distributions at 3.00, 4.20, and 4.88 MeV are given in fig. 19. All the yield curves show a pronounced single resonance at 2.99 MeV and smaller yields in the other region with indication of resonance structure at 4.4 MeV.

The angular distribution on the 2.99 MeV resonance was repeated \( n \) times to make sure of its isotropic behavior. The isotropic character of this angular distribution is of theoretical interest. This point will be discussed later.

\[ 2.10 \quad C^{12}(He^3, p_{11}) N^{1h} \quad (7.03 \text{ MeV state}) \quad \text{Differential cross sections} \]

at \( \Theta_{\text{lab}} = 76^\circ, 109.3^\circ, 146.6^\circ, \) and angular distributions at 4.20 and 4.88 MeV are shown in fig. 20.

There is no pronounced structure in the yield curves, although there is some indication of broad resonance behavior at 4.4 and 4.9 MeV.
3. $^{12}\text{C}(\text{He}^3,\alpha)^{11}\text{C}$ with $\alpha$ groups to the $^{11}\text{C}$ ground state and first excited state at 2.00 MeV

Hinds and Middleton\textsuperscript{21} have published excitation curves from 5.7 to 10.2 MeV at a laboratory angle of $10^0$ and angular distributions at 5.98, 8.83, 9.37, and 10.14 MeV. As in the case of the proton outgoing channels, there are broad resonances in the excitation curves but with resonance positions varying from channel to channel. In these angular distributions of Hinds and Middleton, strong yields were observed in the forward angles, but the measurements extend only up to $120^0$, and hence it is not known whether the yields at backward angles stay small or go up again.

In the present work, differential cross sections at $\theta_{\text{lab}} = 76^0$ and $159.4^0$ from 1.8 to 5.4 MeV and angular distributions at 2.49, 2.88, 2.99, 3.50, 4.20, 4.88 MeV for the $\alpha_0$ group were measured. For the $\alpha_1$ group, differential cross section at $\theta_{\text{lab}} = 76^0$ from 4.0 to 5.4 MeV and angular distributions at 4.2 and 4.88 MeV were measured. The behavior of these two reactions in the present energy region seems somewhat different from their behavior at higher energies as shown in Hinds and Middleton's results.

3.1 $^{12}\text{C}(\text{He}^3,\alpha)^{11}\text{C}$ (ground state): Differential cross sections at $\theta_{\text{lab}} = 76^0$ and $159.4^0$ from 1.8 to 5.4 MeV, at $\theta_{\text{lab}} = 104.5^0$ from 4 to 4.5 MeV, and angular distributions at 2.49, 2.88, 2.99, 3.50, 4.20, 4.88 MeV are shown in fig. 21. The interesting feature of this reaction in the present energy region is the presence of relatively narrow resonances and the rapidly varying angular distributions in these resonance regions. This is shown in the data of 2 to 3 MeV region and around
Figure Captions

Fig. 21. Differential cross sections at laboratory angles 76°, 104.5°, and 159.4°, and angular distributions at 2.49, 2.88, 2.99, 3.50, 4.20, and 4.88 MeV of the reaction \( ^{12}\text{C}(^{3}\text{He}, \alpha)^{11}\text{C} \) (ground state). The solid lines were drawn through the data points. The arrows marked the positions where angular distributions were measured.

Fig. 22. Differential cross sections at laboratory angles 76° and angular distributions at 4.20 and 4.88 MeV of the reaction \( ^{12}\text{C}(^{3}\text{He}, \alpha)^{11}\text{C} \) (2.00 MeV state). The solid lines were drawn through the data points. The arrows marked the positions where angular distributions were measured.

Fig. 23. Results on \( ^{12}\text{C}(^{3}\text{He}, n)^{14}\text{He} \) from Din, Kuan, and Bonner (ref. 13): Excitation curves at laboratory angles 0° and 90°; total cross sections, and angular distributions at 1.87, 2.33, 2.66, 2.87, 3.11, 4.02, 4.63, 4.80, and 5.08 MeV. Notice that the absolute value of the total cross sections was wrong on this graph. The corrected values were shown on fig. 25. The solid lines were drawn through the data points. The dashed lines were theoretical calculations based on the Distorted Wave Born Approximation (from Gibbs and Tobocman, ref. 38).

Fig. 24. Gamma rays from \( ^{12}\text{C}(^{3}\text{He}, p')^{11}\text{He} \)

(a) Excitation curve of the 6.44 MeV gamma ray from \( ^{12}\text{C}(^{3}\text{He}, p^{9} Y_{6.44})^{11}\text{He} \) (6.44 MeV state) with the window setting shown in fig. 5.

(b) Angular distribution of the 6.44 MeV gamma ray at 2.99 MeV resonance. The solid line was the theoretical fit (case 1 of table 2).

(c) Excitation curves of gamma rays with energies greater than about 3 MeV (closed points) and of gamma rays with energies greater than about 4.5 MeV (open circles).
$^12\text{C}(\text{He}^3,\alpha)^{11}\text{C}$ (GROUND STATE)

$\sigma(\theta)_{\text{C.M.}}$ (MB/STERADIAN)

$\theta(\text{Lab})=76^\circ$

$\sigma(\theta)_{\text{LAB}}$ (MB/STERADIAN)

$\theta(\text{Lab})=159.4^\circ$

$\theta(\text{Lab})=104.5^\circ$

Figure 21
Figure 22
Figure 23
4.2 MeV. This suggests compound nucleus formation in this reaction, although it was originally thought to proceed primarily via direct interaction. Notice that the resonance positions in the 159.4° data do not agree with those in the 76° data.

The 4.88 MeV angular distribution has a different shape than the 5.98 MeV distribution of Hinds and Middleton.\(^{21}\)

Another feature of this reaction is the large cross sections compared with the cross sections of other outgoing particle channels.

3.2 \( C^{12}(\text{He}^{3},\alpha_{1})C^{11} \) (2.00 MeV state): Differential cross sections at \( \theta_{\text{lab}} = 76^\circ \) and angular distributions at 4.20 and 4.88 MeV are shown in fig. 22.

There is an indication of a resonance at 4.35 MeV in the yield curve. The angular distribution at 4.88 MeV has a shape similar to the 5.98 distribution of Hinds and Middleton.\(^{21}\)

4. \( C^{12}(\text{He}^{3},n)C^{11} \)

The results of Din, Kuan, and Bonner\(^{13,14}\) are reproduced here for later theoretical discussion. They are given in fig. 23.

The main feature of this reaction is the large difference in the 0° and 90° excitation curves and the rapidly varying angular distributions in the 2 to 3 MeV region. At the time the paper was presented we were very interested in these large variations. Now, from a comparison with the other outgoing channels, we can see that this kind of variation appears in most of the outgoing channels of the He\(^{3}\) induced reactions on C\(^{12}\).

This reaction has been studied by Bromley et al.\(^{19}\) in the 1 to 3
MeV region, Towle and Macefield\textsuperscript{22} from 2 to 5.7 MeV, Fullbright et al.\textsuperscript{23} from 6.5 to 11 MeV. Above 4 MeV, the angular distributions show a consistent forward peaking.

5. Gamma rays from He\textsuperscript{3} induced reactions on C\textsuperscript{12}

The main source of gamma rays from He\textsuperscript{3} induced reactions on C\textsuperscript{12} in the present energy region are those from the decay of residual nuclei N\textsuperscript{14} and C\textsuperscript{11}. The identification of these gamma rays was the subject of a previous work\textsuperscript{17}. In the present work, the main interest was in making more precise measurements on the 6.4 MeV gamma ray in the 3 MeV region. The experimental details were described in the previous chapter. The results will be given below.

In fig. 2\textsubscript{4} are shown the excitation curve of the 6.4 MeV gamma ray at $\theta_{\text{lab}} = 90^\circ$ from 2.7 to 5.4 MeV, the $0^\circ$ excitation curve from 1.2 to 5.4 MeV of all gamma rays with energy greater than 3 MeV, the $90^\circ$ excitation curve from 2.4 to 5.2 MeV of all gamma rays with energy greater than 4.5 MeV and an angular distribution on the 2.99-MeV resonance of the 6.4 MeV gamma ray.

In the 3 MeV region the 6.4 MeV gamma-ray excitation curve has a shape similar to that of $p_g$, as it would be expected. The increase in gamma-ray yield at the higher energies is presumably due to the effect of the 6.23 MeV and other high energy gamma rays. (These gamma rays can appear in the pulse-height analyzer window set for the 6.4 MeV gamma rays). This fact can be more clearly understood if one makes a comparison with the data on the corresponding proton groups. The excitation curve including pulses with energies higher than 3 MeV in the gamma-ray spectrum shows resonances at 1.3, 2.1, 2.45, 3.0, 4.2, 4.4, and 5.1
MeV which appear in the various proton groups.

The angular distribution of the 6.44 MeV gamma ray on the 2.99 MeV resonance has very pronounced structure. Using the same experimental arrangement to measure the angular distributions at other energies did not show pronounced structure. This is because of the fact that this 6.44 MeV gamma ray shows only one strong resonance at 2.99 MeV. This can be compared with the results of the corresponding $p_9$ group.

6. Total neutron cross sections of $^{12}\text{C}^3(\text{He},n)^{11}n$ and $^{11}\text{B}(p,n)^{11}n$

6.1 $^{12}\text{C}^3(\text{He},n)^{11}n$: The total neutron cross sections of $^{12}\text{C}^3(\text{He},n)^{11}n$ from 1.4 to 5.2 MeV is shown in fig. 25. The results in general agree with the old measurement\textsuperscript{13,14}. The reason for remeasuring this total cross section was twofold: first, to check the old results and to extend the measurements down to lower energies to include the threshold; secondly, to check the new experimental method (the method described in section 4 of last chapter is different from the old method and was believed to be better than the old method) so that one could put more faith on the results of the $^{11}\text{B}(p,n)^{11}n$ reaction.

The yield curve shows a broad anomaly from 2.3 to 3.3 MeV with indication of resonance peaks at 2.45, 2.75, and 3 MeV. Since attempts at theoretical analysis were made in this region, this part was measured very carefully and with closely spaced points. The theoretical analysis is given in the next chapter in the discussion of results.

The threshold of $^{12}\text{C}^3(\text{He},n)^{11}n$ in the present measurement appeared at 1.445 $\pm$ 0.010 MeV (fig. 27). It agrees with the values obtained by Bromley et al.\textsuperscript{19} ($E_{th} = 1.449.6 \pm 2.8$ keV) and the recent measurement by Bardin et al.\textsuperscript{21} ($E_{th} = 1.437.5 \pm 0.7$ keV).
6.2 $^1H(p,n)^1H$: The total neutron cross section of $^1H(p,n)^1H$ from 6.3 to 12 MeV is shown in fig. 26. The threshold part of the cross sections is shown in fig. 27.

The yield of $^1H(p,n)^1H$ rises smoothly from threshold up to 8 MeV and then stays nearly constant up to 12 MeV, with broad resonance structure over the whole range of bombarding energies. This is consistent with the results of the many outgoing channels of the $He^3$ on $C^{12}$ reactions where one can see broad resonances scattered over the whole $He^3$ energy range from 2 to 10 MeV. This information gives some general knowledge about the compound nucleus $O^{15}$. The discussion will be given in the next chapter.

The threshold of the $^1H(p,n)^1H$ reaction appeared at $E_{lab} = 6.345 \pm 0.015$ MeV. This determination should be fairly accurate because the analyzing magnet for the 12 MeV tandem accelerator was calibrated before the threshold measurement by making a $C^{13}(p,n)^1H$ threshold measurement. A value of $E_{th} = 3.2352$ MeV was used. Many $(p,n)$ threshold measurements on $C^{13}$, $Al^{27}$, $Cr^{52}$, and $Ni^{58}$, $Ni^{60}$, and $Ni^{62}$ have been made with this magnet. Since these results agree with those of others (e.g. Montague et al. 26) have measured the threshold of $Al^{27}(p,n)$, these measurements may be considered to be a calibration of the analyzing magnet.

Because not many data points were taken in the threshold region it is not possible to quote the threshold energy with smaller uncertainty. In fig. 27, the data in the threshold regions are shown with no background correction in order to show the accuracy of the results.

The total cross section curve had no previous report for
comparison. The threshold energy has been previously reported by Ajzenberg\textsuperscript{27}) using the method of proton recoils in thick nuclear emulsions. The $Q = -6.03 \pm 0.2$ MeV was given. It corresponds to a value of $E_{th} = 6.46 \pm .23$ MeV, which agrees within the experimental error with the present results.
Figure Captions

Fig. 25. Total cross sections of $^{12}\text{C}(\text{He}^3, n)^{14}\text{N}$. The closed points were from the present measurements using a Pilot B scintillator. The open circles were the old data from ref. 13.

Fig. 26. Total cross sections of $^{11}\text{B}(p, n)^{11}\text{Be}$. The solid lines were drawn through the data points with the best guess. The structures below 11 MeV were repeated three times to check the existence with good agreements among runs. The data above 11 MeV were average of two runs. Above 11 MeV, the variations observed in the data points could not be taken as a significant indication of weak structure, and a line was drawn to represent the estimated average cross section behavior. The open circles were the yields from the Ta foil not heated in the nitrogen gas. The closed points were the results having this Ta foil background as well as the room background subtracted.

Fig. 27. Total cross sections near threshold of the reactions $^{12}\text{C}(\text{He}^3, n)^{14}\text{N}$ and $^{11}\text{Be}(p, n)^{11}\text{Be}$. The background was included to show the accuracy of the threshold energies. The threshold energies are $1.445 \pm 0.010$ MeV for $^{12}\text{C}(\text{He}^3, n)^{14}\text{N}$, and $6.345 \pm 0.015$ MeV for $^{11}\text{Be}(p, n)^{11}\text{Be}$.

Fig. 28. Hard sphere phases used in the analyses of the elastic $\text{He}^3 p_1$, and neutron data of the $^{12}\text{C} + \text{He}^3$ reactions. References 31, 47, and 37 were used.
$C^{12}(\text{He}^3, n)O^{14}$

**Figure 25**
Figure 27

$C^{12}(He^3, n)O^{14}$

$N^{14}(p, n)O^{14}$
IV. DISCUSSION OF RESULTS

1. Introduction

Part of the motive for undertaking a large portion of the present work was to search for the answer to the question, brought out in the discussion part of a thesis describing previous preliminary work\textsuperscript{17}, about the nature of the 3 MeV resonance in the gamma-ray excitation curve, and, in particular, which one of the two gamma rays, the 6.44 MeV or the 6.23 MeV gamma ray, was responsible for the resonance and the angular distribution on the resonance. Furthermore, there was no information about the corresponding proton groups available in the literature. It was hoped to find definite experimental facts about this resonance so that an analysis on it could be made in some detail.

In the present work, the contribution of the 6.44 MeV gamma ray to this resonance has been quite clearly established. Measurements of the excitation function and angular distribution of this gamma ray were repeated with better accuracy. The corresponding proton group was also studied experimentally. The results of the proton measurements gave unambiguous support to the results of the gamma-ray investigations. Further measurements on all the other outgoing channels were also obtained with the purpose of providing complete experimental knowledge of the He\textsuperscript{3}-induced reactions on C\textsuperscript{12} in the present energy region.

As the proton group to the 6.44 MeV state and the corresponding 6.44 MeV gamma rays both show a strong isolated resonance at 2.99 MeV He\textsuperscript{3} energy. Angular distributions measured on the resonance show interesting structure. The first attempt was made to interpret these
results based on the compound nucleus theory. So far these analyses
have been quite promising not only in respect to the $p_9$ and $\gamma_{6,14}$ data,
but also to the elastic data and the $p_1$, $n_0$ groups. By further exami-
nation of the experimental results of the other outgoing channels, it
seems likely that some of these outgoing channels also have compound
nucleus formation as a dominant reaction mechanism. It is true that some
of the other outgoing channels do show general trends characteristic of
direct interactions, and the DWBA theoretical interpretation may also be
the possible theoretical ground on which to discuss these reactions.
In the present work, attempts have been made to see how far an analysis
could be carried out on the $\text{He}^3$-induced reactions on $\text{C}^{12}$ assuming pure
compound nucleus formations, and to obtain some predictions of the
properties of the nuclear states.

Furthermore the large partial width of the transition from the
14.5 MeV state of $0^{15}$ to the 6.14 MeV state of $\text{H}^{14}$ indicates the
cluster nature of the nucleus $0^{15}$.

More detailed analysis and discussions are given in the following
separate sections.
2. Analysis of $\text{C}^{12}(\text{He}^3,\text{He}^3)\text{C}^{12}$

The following analysis was mainly for the 2.99 MeV resonance
and the data in the 2 to 3 MeV region.

The analysis was based on the single-level dispersion theory.\textsuperscript{28)}
The differential elastic scattering cross sections for channel spin 1/2
can be written\textsuperscript{29,30)} as

$$\sigma(\theta) = |f_{coh.}|^2 + |f_{inc.}|^2$$
where

\[ f_{\text{coh.}} = -\frac{\eta}{2} C_{\text{sc}}^{2}(\frac{\theta}{2}) \sum_{l} \chi_{l}^{2} e^{i\pi l} C_{l}^{o} \left[ Y_{l}^{0}(\theta) \right] \]

\[ + \frac{(\pi \lambda)^{1/2}}{Z} \sum_{l} (2l+1)^{1/2} e^{i(2\lambda l + \phi_{l})} \sin \frac{\phi_{l}}{2} Y_{l}^{0}(\theta) \]

\[ + \frac{i \pi^{1/2}}{Z} \sum_{l} \frac{1}{(2l+1)^{1/2}} \left[ (l+1) K_{l}^{+} + l K_{l}^{-} \right] Y_{l}^{0}(\theta), \]

\[ f_{\text{inc.}} = \frac{i \pi^{1/2}}{Z} \sum_{l} \left[ \frac{1}{2l+1} \right] \left[ l K_{l}^{+} - l K_{l}^{-} \right] Y_{l}^{1}(\theta), \]

\[ K_{l}^{\pm} = e^{2i(\alpha_{l} + \phi_{l})} \sum_{j} \frac{\Gamma_{j}}{\Gamma_{j}^{\pi}} \left[ 1 - e^{2i\beta_{j}^{\pi}} \right] \gamma_{j} \lpm \]

and

\[ \beta_{j}^{\pi} = \tan^{-1} \left[ \frac{\Delta_{j}^{\pi/2}}{E_{j}^{\pi} - E} \right], \]

The symbols are defined in the appendix. The actual calculations were performed using the IBM 709 computer program used by Brown in his Ca^{40}(p,p)Ca^{40} calculation. The two reactions Ca^{40}(p,p)Ca^{40} and C^{12}(He^{3},He^{3})C^{12} have the same channel spin 1/2. A hand calculation, using a graphical method, was made to check the correctness of the program.

The hard sphere phases \( \phi_{l} \) were obtained from a least square fit to the tabulated values. They are plotted in fig. 28a. For the 2.99 MeV resonance the resonance energy and width were obtained from the p_{9} and 6.44 MeV gamma-ray excitation curves. The J^{\pi} and \( \ell \) values and the resonance positions and widths of the 2.75 and 2.45 MeV resonances were from the analysis of the total cross sections and angular distributions of the reactions C^{12}(He^{3},n)O^{14} and C^{12}(He^{3},p_{1})N^{14}. 
(2.31 MeV state) which will be discussed in later sections.

A set of standard shapes for single isolated resonances for each $\ell$ and $J^{\pi}$ at 3.0 MeV was first calculated, shown in fig. 29. By comparing them with the experimental data one can make some initial guess of the parameters. The final parameters used for the curves in fig. 10 and given in table 1 were chosen after many trial calculations.

<table>
<thead>
<tr>
<th>Curves</th>
<th>$E_R$ (lab) (MeV)</th>
<th>$\Gamma_{lab}$ (keV)</th>
<th>$\ell$</th>
<th>$J^{\pi}$</th>
<th>$\Gamma_{He^3}/\Gamma$</th>
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<tr>
<td>Solid Line</td>
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<td></td>
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<td></td>
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<tr>
<td>(Fit 1)</td>
<td>2.99</td>
<td>125</td>
<td>2</td>
<td>$5/2^+$</td>
<td>0.15</td>
</tr>
<tr>
<td>dashed line</td>
<td>2.99</td>
<td>125</td>
<td>2</td>
<td>$5/2^+$</td>
<td>0.15</td>
</tr>
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<td>(Fit 2)</td>
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<td>420</td>
<td>0</td>
<td>$1/2^+$</td>
<td>0.05</td>
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<tr>
<td></td>
<td>2.45</td>
<td>200</td>
<td>1</td>
<td>$3/2^-$</td>
<td>0.10</td>
</tr>
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</table>

The use of $J^{\pi} = 5/2^+$ for the 2.99 MeV resonance is consistent with the analysis of the 6.4 MeV gamma-ray angular distribution, which will be discussed in a later section. The results of the calculation show that the fitting to the 2.99 MeV resonance is quite successful. From the data at 164.5°, fig. 10, one can see that a resonance at 2.45 MeV is essential in order to improve the fit. But the deviation of the calculated values from the experimental data in the 2.75 MeV region at
Figure Captions

Fig. 29. Standard $^1\text{C}^{12}(\text{He}_3^3,\text{He}_3^3)^1\text{C}^{12}$ resonance shapes calculated at $E_0 = 3.00 \text{ MeV}$, $I^* = 125 \text{ keV}$. The hard sphere phases shown in fig. 28a were used. The Rutherford (dashed lines) and Rutherford plus hard sphere (line-dot-line) calculated potential, scattering cross sections are shown in the figure. The value of unity was used for the ratio of the elastic partial width to the total width.

Fig. 30. Theoretical fits of the total cross sections of the reactions $^1\text{C}^{12}(\text{He}_3^3,n)^1\text{He}_4^4$, $^1\text{C}^{12}(\text{He}_3^3,p_1^1)^1\text{He}_4^4$, and $^1\text{C}^{12}(\text{He}_3^3,p_0^0)^1\text{He}_4^4$. The parameters used are given in table 4. The experimental data points for $(\text{He}_3^3,n)$ are the same as those in fig. 25. The $(\text{He}_3^3,p_1^1)$ and $(\text{He}_3^3,p_0^0)$ points were taken from the excitation curves of Johnston et al. (ref. 20).

Fig. 31. Theoretical fits of the angular distributions of $^1\text{C}^{12}(\text{He}_3^3,p_1^1)^1\text{He}_4^4$ and $^1\text{C}^{12}(\text{He}_3^3,n)^1\text{He}_4^4$. The parameters are those given in table 5. The data for $p_1^1$ were from the present measurement (fig. 12), those for neutron were from the results of Din, Kuan, and Bonner (ref. 13 and fig. 23). The same hard sphere phases were used as are shown in figs. 28b and 28c.

Fig. 32. Angular distributions of $^1\text{C}^{12}(\text{He}_3^3,p_1^1)^1\text{He}_4^4$ (2.31 MeV state) from 2 to 5 MeV in about 50 keV steps, taken from the six excitation curves of Johnston et al. (ref. 20). The data points of Johnston et al. were transformed to the C.M. system. The lines were drawn through the experimental points.
Figure 30
Figure 31
$^{12}\text{C}(\text{He}^3, p)N^{14}$

Points taken from Johnston et al.

Figure 32
16h.5° has not been successfully explained. Furthermore there is no sure explanation for the large deviation of the data from the Rutherford cross section in the low and high energy region. The Rutherford cross sections are shown in fig. 10. No attempt has yet been made to analyze the data elsewhere than in the 2 to 3 MeV region, although there is evidence for resonances at 4.2 and 5.1 MeV. In fact, the primary reason for the analysis of the elastic data was an interest in the determination of the l value for the 2.99 MeV resonance and in a check of the consistency of the parameters for the 2.15 and 2.75 MeV resonances obtained from the analysis of the reaction \( \text{C}^{12}(\text{He}^3,\text{n}_\circ)\text{C}^{11}_\bullet \) and \( \text{C}^{12}(\text{He}^3,\text{p}_\circ)\text{N}^{11}_\bullet \) (2.31 MeV state). The small elastic partial width values required to fit the data can be understood from the large cross sections in the many other open channels.

3. Analysis of the 6.44 MeV gamma-ray angular distribution from \( \text{C}^{12}(\text{He}^3,\text{p}_\circ\gamma)\text{N}^{11}_\bullet \) (6.44 MeV state)

The above experimental results show that the resonance at 2.99 MeV \( \text{He}^3 \) energy in the gamma-ray excitation curve and the gamma-ray angular distribution taken at the resonance are mainly due to the 6.44 MeV gamma rays. The analysis given below was for this 6.44 MeV gamma-ray angular distribution.

The analysis was based on the expression for the angular distribution of a two-stage particle reaction followed by gamma-ray emission, \((a,b\gamma)\), as given by Kraus et al.\(^{33}\). Assuming isolated resonances, the cross section can be expressed, for the present case, as

\[
\sigma(\theta) = \sum_{s'_1 s'_2 \Delta} a(s_1 s_2) (-1)^\lambda F(\Delta) P_\Delta (\cos\theta)
\]
where
\[ F(\Delta) = (2 S'_1 + 1)^{1/2} (2 S'_2 + 1)^{1/2} C(L, L, l, -l; \Delta, 0) Z(l J \ell j; s \Delta) \]
\[ \times W(j S_1^i j S_2^i l \Delta) W(S'_1 j S'_2 j j_B \Delta) W(j L l J j_f \Delta) \]
\[ \lambda = -\frac{\Delta}{2} + l' + s + S' - S' + j_B - j_f \]

The definition of symbols is as follows.

- \( S_1', S_2' \) = outgoing channel spins with relative amplitudes
  \[ \alpha_{S'} = \frac{1}{2}, \quad S' = j_B + j_f \]
  \( S = \frac{3}{2}, \quad S_2 = \frac{7}{2} \)
- \( S = \) incoming channel spin = 1/2
- \( \ell \) = relative orbital angular momentum of incident particle = 2 (from analysis on elastic He\(^3\) data)
- \( J \) = spin of compound nucleus = 5/2
- \( \ell' \) = relative orbital angular momentum of outgoing particle
- \( j_B \) = spin of outgoing particle = 1/2
- \( J \) = spin of \( \gamma \) emitting state = 3
- \( L \) = multipolarity of \( \gamma \) radiation = 2
- \( j_f \) = spin of final state = 1
- \( \Delta \) = subscript of Legendre polynomials

In general there is no coherent interference between outgoing \( \ell \) values, if the gamma-ray distribution alone is observed. Such interference would exist only if the \( p' - \gamma \) correlation were to be studied. Coherent interference does exist, however, on the two outgoing channel spins \( S_1' \) and \( S_2' \). The relative phases of the outgoing channel spin amplitudes is expected to be 0 or \( \pi \). The actual calculation was first done by using IBM 650 computer. Since the least square fit of the experimental data

* The help of Dr. J.P. Schiffer on the program and computation is greatly appreciated.
show no significant contribution from $P_6$ term, the angular distribution is essentially symmetric about $90^0$ and the highest observed term is $P_4$. From general considerations the incident $\lambda \geq 2$ and the compound $J \geq 5/2$ (the $Z$ coefficient for $\triangle = 4$, $J_1 = J_2 = J$, $S = 1/2$ is non-zero only for $\lambda \geq 2$ and $J \geq 5/2$). The first computation was made for all possible cases of $\lambda$, $j$, $\lambda'$, $S'$ for $\lambda \geq 2$, $J \geq 5/2$ and for both the $3^+$ and $3^-$ cases for the 6.44 MeV state of $^7\text{Li}$. The computer results were checked by hand calculation using the table$^{32}$ of $Z$ and $W$ coefficients. Since the later experiments on elastic $\text{He}^3$ scattering determined the value of $\lambda$ to be 2, only the cases for $\lambda = 2$ are given in table 2. Case 1 is the final fit used in fig. 24.

Table 2
Calculated Angular Distribution of the 6.44 MeV Gamma-rays

<table>
<thead>
<tr>
<th>Case No.</th>
<th>$\lambda$</th>
<th>$J^\pi$</th>
<th>$\lambda'$</th>
<th>$S'$</th>
<th>$3^+$ cases</th>
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<tr>
<td>1</td>
<td>2</td>
<td>5/2$^+$</td>
<td>0</td>
<td>5/2$^+$</td>
<td>$P_0 + .490 P_2 - .299 P_4$</td>
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<td>2</td>
<td>2</td>
<td>5/2$^+$</td>
<td>2</td>
<td>5/2$^+$</td>
<td>$P_0 + .049 P_2 + .150 P_4$</td>
</tr>
<tr>
<td>3</td>
<td>2</td>
<td>5/2$^+$</td>
<td>2</td>
<td>7/2$^+$</td>
<td>$P_0 + .204 P_2 + .150 P_4$</td>
</tr>
<tr>
<td>4</td>
<td>2</td>
<td>5/2$^+$</td>
<td>2</td>
<td>5/2$^+, 7/2^+$</td>
<td>$- .120 P_2$</td>
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</table>

$3^-$ cases

<table>
<thead>
<tr>
<th>Case No.</th>
<th>$\lambda$</th>
<th>$J^\pi$</th>
<th>$\lambda'$</th>
<th>$S'$</th>
<th>$3^-$ cases</th>
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<td>5/2$^-$</td>
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<td>5/2$^+$</td>
<td>1</td>
<td>7/2$^-$</td>
<td>$P_0 + .437 P_2 - .192 P_4$</td>
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<td>2</td>
<td>5/2$^+$</td>
<td>1</td>
<td>5/2$^-, 7/2^-$</td>
<td>$- .094 P_2 + .191 P_4$</td>
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</tbody>
</table>
It should be remarked that from the analysis of the gamma-ray data alone it is not possible to determine the values of \( \mathcal{L} \) and \( J \) uniquely and to choose between \( 3^+ \) and \( 3^- \) for the 6.44 MeV state of \( ^{11}\text{Li} \). There are many other possible values of \( \mathcal{L} \) different from 2 which could be made to fit the gamma-ray data. But the analysis of gamma-ray angular distribution gives a check on the results obtained from the analysis of the elastic \(^3\text{He}\) and \( p_9 \) data. And, in fact, the choice of \( 5/2^+ \) instead of \( 3/2^+ \) for the compound \( J^{\pi} \) in the elastic scattering cross section analysis was based on the analysis of gamma-ray angular distribution. It is a fact that the analysis of elastic data is sensitive to the determination of \( \mathcal{L} \) values but is not sensitive in the choice of \( J \) values for a given \( \mathcal{L} \) value (cf. the standard resonance shapes, shown in fig. 29, for the cases \( \mathcal{L} = 2, J^{\pi} = 3/2^+ \), and \( \mathcal{L} = 2, J^{\pi} = 5/2^+ \)).

4. Analysis of \(^{12}\text{C}(\text{He}^3, p_9)^{11}\text{Li}^{*} (6.44 \text{ MeV state})\)

The analysis of the angular distribution of \(^{12}\text{C}(\text{He}^3, p_9)^{11}\text{Li}^{*} \) was based on Equations (3.10), (4.5), and (4.6) of Blatt and Biedenharn\(^{28}\) which were derived on the basis of single-level dispersion theory. The expressions for the reaction cross section actually used was\(^{9}\)

\[
\sigma(\theta) = \sum_{S'S'L} (-1)^{S+L} \sum_{J_1 J_2 J_3 \rho_1 \rho_2} \frac{Z(l_1 J_1 l_2 J_2 ; S L) Z(l'_1 J_1 l'_2 J_2 ; S'L)}{\pi^{L}} \left[ \cos \left( \sigma_{e_1} + \phi_{e_1} + \phi_{e_1'} + \phi_{e_2'} + \beta_1 - \phi_{e_2} - \phi_{e_2'} - \phi_{e_2'} - \beta_2 \right) \right]
\]

\[
\times \left( \frac{\Gamma_1}{\Gamma_1'} \right)^{1/2} \left( \frac{\Gamma_2}{\Gamma_2'} \right)^{1/2} \left[ \left( \frac{E - E_1}{\Gamma_1/2} \right)^{1/2} \right] \left[ \left( \frac{E - E_2}{\Gamma_2/2} \right)^{1/2} + 1 \right] \left( \frac{\Gamma_1}{\Gamma_1'} \right)^{1/2} \left( \frac{\Gamma_2}{\Gamma_2'} \right)^{1/2} .
\]
The symbols are defined in the appendix. This expression for reaction cross section includes the interference terms between levels which are separated by at least their level widths and whose spins or parities are different\textsuperscript{34}).

For the single resonance at 2.99 MeV He\textsuperscript{3} energy of the reaction C\textsuperscript{12}(He\textsuperscript{3},p)He\textsuperscript{14}\textsuperscript{*} (6.44 MeV state), we have \( i = 1/2; \ I = 0; \ S = 1/2; \) \( S' = 5/2, 7/2; \) \( E = E_o = 2.99 \) MeV, \( J_1^{\pi} = J_2^{\pi} = 5/2^+; \) \( \ell_1 = \ell_2 = \ell = 2; \) \( \ell_1' = \ell_2' = \ell'; \) where the \( \ell \) and \( J^{\pi} \) values are the results of elastic data analysis. The expression for the reaction cross section then reduces to

\[
\sigma(\theta) = \sum_{s'\ell} \frac{(-1)^{s'-\frac{1}{2}}}{2 \ k^2} \sum_{\ell'} \kappa(2, \frac{5}{2}, 2, \frac{5}{2}; \frac{1}{2}, L) Z(\ell', \frac{5}{2}, \ell' \frac{5}{2}; s'L') P_\ell' (\cos \theta) \left( \frac{\Gamma_{He^3}^Z}{\Gamma} \right) \left( \frac{\Gamma_{He^3}}{\Gamma} \right).
\]

The approach in fitting the data was to calculate angular distributions for individual \( S' \) and for the lowest one or two \( \ell' \) values and to compare them with the experimental data. Hand calculations were made using the available table\textsuperscript{35}) of \( Z \) coefficients. Since it has already been determined from the analysis of the elastic data that \( J^{\pi} = 5/2^+ \) and that the incoming \( \ell = 2 \) for the 2.99 MeV resonance, only the cases for \( \ell = 2, \ J^{\pi} = 5/2^+ \) are given in table 3.
Table 3

Calculated angular distributions of $^4{}^{12}\text{(He}_3^3, p_0)^7\text{Li}^*$

(6.44 MeV state) at 2.99 MeV resonance

<table>
<thead>
<tr>
<th>No.</th>
<th>$S$</th>
<th>$\ell$</th>
<th>$J^\pi$</th>
<th>$\ell'$</th>
<th>$S'$</th>
<th>$3^+$ case</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1/2$^+$</td>
<td>2</td>
<td>5/2$^+$</td>
<td>0</td>
<td>5/2$^+$</td>
<td>$P_0$</td>
</tr>
<tr>
<td>2</td>
<td>1/2$^+$</td>
<td>2</td>
<td>5/2$^+$</td>
<td>2</td>
<td>5/2$^+$</td>
<td>$P_0 - .407 P_2 + .550 P_4$</td>
</tr>
<tr>
<td>3</td>
<td>1/2$^+$</td>
<td>2</td>
<td>5/2$^+$</td>
<td>2</td>
<td>7/2$^+$</td>
<td>$P_0 - .693 P_2 - .164 P_4$</td>
</tr>
</tbody>
</table>

3$^-$ case

<table>
<thead>
<tr>
<th>No.</th>
<th>$S$</th>
<th>$\ell$</th>
<th>$J^\pi$</th>
<th>$\ell'$</th>
<th>$S'$</th>
<th>$3^-$ case</th>
</tr>
</thead>
<tbody>
<tr>
<td>4</td>
<td>1/2$^+$</td>
<td>2</td>
<td>5/2$^+$</td>
<td>1</td>
<td>5/2$^-$</td>
<td>$P_0 + .913 P_2$</td>
</tr>
<tr>
<td>5</td>
<td>1/2$^+$</td>
<td>2</td>
<td>5/2$^+$</td>
<td>1</td>
<td>7/2$^-$</td>
<td>$P_0 + .286 P_2$</td>
</tr>
</tbody>
</table>

By a comparison of the calculated angular distributions, given in table 3, and the isotropic experimental angular distribution, the only possibility is that of $\ell' = 0, S' = 5/2^+$. An admixture of d-wave for the outgoing particle is not necessary. The final calculated angular distribution is isotropic, and the cross section is given by

$$\sigma(\theta) = 6.7 P_0 \text{mb/sterad},$$

using $\left(\frac{|\Pi_{4,5}^3|^2}{\Gamma}\right)\left(\frac{\Gamma_{p_9,0}}{\Gamma}\right) = 0.062, S' = 5/2^+, \ell' = 0$. Comparison between theory and experiment is shown in fig. 19 where the solid line is the final calculated distribution. Agreement is seen to be good.
As the $\frac{\Gamma_{He^3} \Delta}{\Gamma} = 0.15$ has been obtained from the calculation of elastic cross section, we have $\frac{\Gamma_{p_1}}{\Gamma} = 0.413$ and $p_9$ partial width is 51.5 keV ($\Gamma' = 125$ keV).

From the above analysis, one comes to a conclusion that the parity of the 6.44 MeV state of $^1H$ is even. This assignment of the parity for this state has not previously been reported in the literature.

5. Total cross sections of the reactions $^1H(He^3,n)O^{1h}$, $^1H(He^3,p_1)N^{1h^*}$ and $^1H(He^3,p_0)N^{1h}$

The purpose of the analysis discussed in this section was to assign resonance parameters to be used in the analysis of angular distributions. The total cross sections for the emission of $p_0$ and $p_1$ were obtained from the differential cross sections at six angles, $\theta_{lab} = 7^\circ, 30^\circ, 60^\circ, 90^\circ, 120^\circ, 150^\circ$, measured by Johnston et al. 20).

The Breit-Wigner single-level resonance formula for the total cross section for the $(\hat{\alpha}, \hat{\beta})$ reaction can be expressed\(^ {36}\) as

$$\sigma(\hat{\alpha}, \hat{\beta}) = \sum_{s,s'} \sigma(s, s')$$

where $\hat{\alpha}$ and $\hat{\beta}$ is the group of incoming and outgoing channels respectively, and

$$\sigma(s, s') = \frac{1}{\pi} \frac{2J + 1}{(2J_1 + 1)(2J + 1)} \frac{\Gamma_{s \rightarrow \ell}}{\ell} \frac{\Gamma_{s' \rightarrow \ell'}}{\ell'} \frac{(E - E_0)^2 + (\Gamma')^2}{(\Gamma_{s \rightarrow \ell})^2}$$

The widths $\Gamma_{s \rightarrow \ell}$ and $\Gamma_{s' \rightarrow \ell'}$ are the partial widths for formation in channel $\alpha_s$ and decay in channel $\beta_{s'}$ with orbital angular momentum $\ell$ and $\ell'$. $\Gamma$ is the total width. $E_0$ is the resonance energy. Since it is in general impossible to obtain information about $\Gamma_{s \rightarrow \ell}$ or $\Gamma_{s' \rightarrow \ell'}$ from the analysis of the total cross section data, the form representing
sum over $S, S', \ell$ and $L'$ was used:

$$
\sigma(\bar{\alpha}, \bar{\beta}) = \prod_{\lambda} \frac{x_{\lambda}^{2}}{(2i+1)(2i'+1)} \frac{\Gamma_{\lambda}}{(E-E_{0\lambda})^{2} + (\Gamma_{\lambda}/2)^{2}} \frac{\Gamma_{\lambda}}{(E-E_{0\lambda})^{2} + (\Gamma_{\lambda}/2)^{2}}
$$

where

$$
\Gamma_{\lambda} = \sum_{S, \ell} \Gamma_{S \ell \lambda}, \quad \Gamma_{\lambda}' = \sum_{S', \ell'} \Gamma_{S' \ell' \lambda}'.
$$

The form of this expression representing the sum over resonances which are denoted by the subscripts $\lambda$ is:

$$
\sigma(\bar{\alpha}, \bar{\beta}) = \prod_{\lambda} \frac{x_{\lambda}^{2}}{(2i+1)(2i'+1)} \sum_{\lambda} \left( 2 \Gamma_{\lambda} \right) \frac{\Gamma_{\lambda}}{(E-E_{0\lambda})^{2} + (\Gamma_{\lambda}/2)^{2}} \frac{\Gamma_{\lambda}}{(E-E_{0\lambda})^{2} + (\Gamma_{\lambda}/2)^{2}}
$$

This form was then programmed for an IBM 1401 computer, in the following manner:

$$
\sigma_{T} = \sum_{\lambda} \frac{\sigma_{T\lambda}}{E_{0\lambda}} \quad \text{where}
$$

$$
\sigma_{T\lambda} = \text{contribution to the total cross section from the single resonance } \lambda \text{ at the resonance energy } E_{0\lambda}.
$$

Thus, from the computer calculation one can obtain the best set of values on $E_{0\lambda}$, $\Gamma_{\lambda}$ and $\sigma_{T\lambda}$. If the $J_{\lambda}$ value is known for a resonance, the $\frac{\Gamma_{\lambda}}{\Gamma_{\lambda}}$ can be calculated from $\sigma_{T\lambda}$.

The final parameters used for the curves in fig. 30 are given in table 4.

No attempts were made to fit the cross sections at high energies because it was felt some other reaction mechanism would probably become important at higher energies as indicated by the experimental data. The two resonances at 4.60 and 5.10 MeV for $p_{0}$ group was put in to give a
continuous background to the lower energies.

Table 4

Parameters used in fits on total cross sections of $^{12}\text{(He}^3,n)\text{O}^{11\hbar}$, $^{12}\text{(He}^3,p_1)\text{H}^{11\hbar\times}$ and $^{12}\text{(He}^3,p_0)\text{H}^{11\hbar}$

<table>
<thead>
<tr>
<th>$E_{\alpha\lambda}$ (MeV)</th>
<th>$\Gamma_{\lambda}$ (keV)</th>
<th>$\sigma_{T\lambda}$ (mb)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>$n_0$</td>
</tr>
<tr>
<td>2.45</td>
<td>200</td>
<td>17.5</td>
</tr>
<tr>
<td>2.75</td>
<td>420</td>
<td>20.0</td>
</tr>
<tr>
<td>2.99</td>
<td>125</td>
<td>8.0</td>
</tr>
<tr>
<td>3.28</td>
<td>280</td>
<td>0</td>
</tr>
<tr>
<td>3.60</td>
<td>500</td>
<td>0</td>
</tr>
<tr>
<td>4.60</td>
<td>480</td>
<td>0</td>
</tr>
<tr>
<td>5.10</td>
<td>680</td>
<td>0</td>
</tr>
</tbody>
</table>

6. Comparison of the reactions $^{12}\text{(He}^3,p_1)\text{H}^{11\hbar\times}$ and $^{12}\text{(He}^3,n)\text{O}^{11\hbar}$

These two reactions show a high degree of symmetry of the same type. They have a common incoming channel. The final states (2.31 MeV states of $\text{H}^{11\hbar}$ and ground state of $\text{O}^{11\hbar}$) are members of an isobaric triplet with $J^\pi = 0^+$ and $T = 1$. The Coulomb force in the case of $p_1$ and the outgoing particle energies are the respects in which the reactions differ. In fact, the experimental results of these two reactions are indeed quite similar, as can be seen by comparing the $90^\circ$ and $0^\circ$ yield curves from
2 to 5 MeV$^{11,20}$, the 10° yield curves and angular distributions from 5.7 to 11 MeV$^{23}$, and the total cross sections shown in fig. 30.

The interpretation of the rapidly varying angular distributions in the 2 to 3 MeV region using the single-level resonance formula, used in the analysis of p$_9$ data, is given below. Unlike the case of p$_9$, the interference between resonances having different J or \( \pi \) has to be taken into account in the p$_1$ and n$_0$ cases. The expression for the reaction cross section was programmed for an IBM 709 computer for the single-channel-spin case, which is the case for the present two reactions. Entries for 10 resonances of different J \( \pi \)'s are provided. The hard sphere phases \( \phi_L \)'s used for the incoming He$^3$ particles was the same as those used in elastic He$^3$ analysis. The \( \phi_{L'} \)'s of the outgoing protons were calculated using a program originally written by Dr. R. W. Harris$^{47}$. The values used in the computation are plotted in fig. 28b. The \( \phi_{L'} \)'s of the outgoing neutrons were obtained by a least square fit of the tabulated values$^{37}$. The values used in the computation are plotted in fig. 28c.

The number of angular distributions one wants to calculate is controlled from input cards. The output includes coefficients of Legendre polynomials, cross sections at the angles one wants, and a rough plot. The parameters used for the three resonances were from the analysis of elastic He$^3$, p$_9$ data, and the total cross sections of p$_1$ and n$_0$. The values of \( \frac{P_{\omega \lambda} P_{\phi \lambda}}{\Gamma_{\lambda}^2} \) for different J \( \pi \)'s were computed from the \( \sigma_{\tau \lambda} \) values in the total cross section analysis. These parameters were adjusted many times until the fits to both the total cross
sections and the angular distributions were reasonably good when compared with the experimental data. The final parameters used for the fits, shown in fig. 31 are given in table 5.

Table 5
Parameters used in fits of the angular distributions shown in fig. 31

<table>
<thead>
<tr>
<th>$E_0$ (MeV)</th>
<th>$\Gamma_{\text{lab}}$ (keV)</th>
<th>$J^\pi$</th>
<th>$\frac{\Gamma_{\text{He}^3 P_1}}{\Gamma^2}$</th>
<th>$\frac{\Gamma_{\text{He}^3 Q_0}}{\Gamma^2}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.99</td>
<td>125</td>
<td>$5/2^+$</td>
<td>0.00512</td>
<td>0.00585</td>
</tr>
<tr>
<td>2.75</td>
<td>420</td>
<td>$0^+$</td>
<td>0.02823</td>
<td>0.4035</td>
</tr>
<tr>
<td>2.45</td>
<td>200</td>
<td>$3/2^-$</td>
<td>0.01303</td>
<td>0.01572</td>
</tr>
</tbody>
</table>

It should be remarked that the use of $0^+$ for the 2.75 MeV resonance gives a much better fit than any other $J^\pi$, while the use of $3/2^-$ or $1/2^-$ for the 2.45 MeV resonance has not much effect on the shapes of the angular distributions above 2.3 MeV.

It is probably worthwhile to mention that many hand calculations were tried to check the computer results and to confirm the assignments. The parameters obtained from the analyses of the total cross section were used in the expression for the differential reaction cross section, which was as follows:
\[
\sigma(\theta) = \frac{1}{4\pi} \sum L P_L(\cos \theta) \left\{ \sum_{J_1, J_2, L_1, L_2} \frac{\epsilon^2(\epsilon_1 J_1, \epsilon_2 J_2, J_1 L_1, J_2 L_2)}{\sqrt{2J_1 + 1} \sqrt{2J_2 + 1}} \right\}
\]

\[
\times \frac{C_{03}(ARG)}{\left[ \left( \frac{E_2 - E_1}{m_2^2} \right)^2 + 1 \right]^{1/2} \left[ \left( \frac{E_2 - E_1}{m_2^2} \right)^2 + 1 \right]^{1/2}} \times \sqrt{\sigma_{T1}} \sqrt{\sigma_{T2}}
\]

A table of \( A \)'s for \( L \) values from 0 to 8 and for all the possible \( J \ \Pi \) values was made. The term \( C \) was fixed from the fits to the total cross sections. Tables were made of calculated values of \( B \) for many He\(^3\) energies. Then the sum in the square bracket was carried out to compare the calculated Legendre coefficients with those obtained from the experimental data. This kind of work can give one some insight into how good the fit is. For example, the choice of \( 0^+ \) for the 2.75 MeV resonance is quite convincing when one examines the tables of \( A \) and \( B \) values.

Since the angular distributions above 4.5 MeV show consistent peaking forward which indicates the possibility of \( L = 0 \) double stripping, no attempt was made to extend the above analysis to higher energies. Gibbs and Tobocman\(^{38}\) have made some DWBA calculations (see fig. 23) for \(^{12}\)C(He\(^3\),n)\(^{14}\)N in the 2 to 5 MeV region. However, from the
comparison with the experimental results, it seems that the present interpretation of the rapidly varying angular distributions is quite successful.

To provide more experimental information, the angular distributions of $^1T(He^3, p_4)^{14N*}$ in the 2 to 5 MeV region in about 50 keV steps were plotted in fig. 32. They were obtained from the 6 excitation curves measured by Johnston et al.\textsuperscript{20).} The ratios of the coefficients of Legendre polynomials obtained from least square fits of the above angular distributions are shown in fig. 33. The crosses in the figure are from the present measurements.

7. Other outgoing channels.

No detailed analysis has been made of other outgoing channels than the above mentioned ones. Only some general discussions are given below.

Angular distributions of $p_0$ from 2 to 5 MeV with about 50 keV steps were plotted in fig. 34. They were obtained from the 6 excitation curves measured by Johnston et al.\textsuperscript{20).} The ratios of the Legendre coefficients of these angular distributions (from least square fits) are shown in fig. 35. The shapes of the angular distributions are different at 2, 3, 4.2, and 5 MeV regions. This is true even at higher energies\textsuperscript{21).} This reaction $^1T(He^3, p_0)^{14N}$ has two possible outgoing channel spins. It appears quite interesting to extend the present single channel spin analysis to the double spin case of $O^T(He^3, p_0)^{14N}$. It is true the analysis will be more complicated. The $P_3$, $P_4$, $P_5$, $P_6$ groups also show narrow resonances in the excitation curves and varying angular distributions, which suggest the process of
Figure Captions

Fig. 33. Ratio of Legendre coefficients representing the $C^{12}(\text{He}^3, p_1)N^{14*}$ angular distributions. The dots represent the least square fits to the data shown in fig. 32 (ref. 20), and the crosses represent the least square fits to data of the present measurements (fig. 12).

Fig. 34. Angular distributions of $C^{12}(\text{He}^3, p_0)N^{14}$ from 2 to 5 MeV in about 50 keV steps taken from the six excitation curves of Johnston et al. (ref. 20). The data points of Johnston et al. were transformed to the C.M. system. The solid lines were drawn through the experimental points.

Fig. 35. Ratio of Legendre coefficients representing the $C^{12}(\text{He}^3, p_0)N^{14}$ angular distributions. The dots represent the least square fits of the data shown in fig. 34 (ref. 20), and the crosses represent the least square fits to the data of the present measurements (fig. 11).

Fig. 36. Summary of all the experimental results in the previous figures. The dashed lines are the excitation curves at 76°. The energy values of $^{0}\text{I}_5$ are from table 7.
Points taken from Johnston et al.

$^{12}\text{C}(^{3}\text{He},^{6}\text{Li})^{14}\text{N}$

C.M. ANGLE (DEGREES)

W/B (MEV)

G.0
compound nucleus formation. Again, many of them have two possible outgoing channel spins. It is interesting to point out that the $p_g$ channel has forward peaking in all the angular distributions. This seems to be the case also for the $p_2$ channel except at 4.88 MeV where the angular distribution shows resonance structure.

For the $\alpha_0$ channel, the pronounced resonance structure in the excitation curves and the varying angular distributions in the 2 to 3 MeV region indicate the presence of compound nucleus formation in this region. This reaction $^{12}\text{C}(\text{He}^3, \alpha_0)^{11}$ has also two possible outgoing channel spins. It is interesting to point out that the shapes of angular distributions at 4.2 and 4.88 MeV are similar to those of $^{11}\text{Be}(\text{He}^3, \alpha)^{10}$ where the excitation curves do not show resonance structure.

Newns has discussed the stripping of two nucleons such as $(\text{He}^3, p)$ reactions. He pointed out that the behavior of these reactions is related to the configurations of the nuclear excited states. It is hoped that the present results on all the $(\text{He}^3, p)$ reactions from $^{12}\text{C}$ target can provide some information for the theoretical study in this direction.

8. Total cross sections of $^{11}\text{Be}(p, n)^{11}\text{Be}$

As in the case of the $^{12}\text{C}+\text{He}^3$ reactions, no sharp resonances are found in the $^{11}\text{Be}(p, n)^{11}\text{Be}$ reaction. Indication of broad resonances can be found at $E_p = 7.5$, 7.7, 7.95, 8.20, 9.05, 9.4, and 9.85 MeV. The 9.85 MeV one is relatively more pronounced than the others. The estimated resonance parameters for this resonance are $E_0 = 9.85 \pm 0.05$ MeV, $\Gamma_{lab} = 600 \pm 100$ keV, after subtracting out the continuous yield.
The accurate threshold measurement of this reaction has special significance in connection with the conserved-vector-current theory as mentioned in the Introduction. From an accurate determination of the ft value of the $O^+ \rightarrow O^+$ positron transition $0^{1h}(\tau^+, \nu) N^{1h*}$ (2.311 MeV state) a value is obtained for the vector coupling constant $G_v$ which, according to the conserved-vector-current hypothesis, should equal the coupling constant $G_{\mu e}$ in muon decay. Because of the experimental difficulty in obtaining a sufficiently accurate determination of the positron end-point energy from beta spectra measurement\textsuperscript{11,12}, the mass difference of $O^{1h}$ and $N^{1h*}$, the parent and daughter state of the $\beta^+$ decay, have been measured by indirect methods. Bromley\textsuperscript{19} and a group at the Naval Research Laboratory\textsuperscript{43} have calculated this end-point energy from the threshold measurement of $C^{12}(He^3, n)O^{1h}$ and the other known masses and Q values. Their final values have large uncertainties due to the uncertainties of the various masses and Q values they used. Bardin\textsuperscript{24} has improved the method by making accurate measurements of the $Q_n$ and $Q_{p1}$ values of the reactions $C^{12}(He^3, n)O^{1h}$ and $C^{12}(He^3, p_1) N^{1h*}$ (2.311 MeV state) directly.

$$E_{\text{max}} (\beta^+) = (O^{1h} - N^{1h*}) c^2 - 2m_e c^2$$

$$= Q_{p1} - Q_n + (N^1 - n) c^2 - 2m_e c^2$$

In this way they eliminated the use of many other uncertain quantities. The $N^{1h}(p, n)O^{1h}$ threshold measurement would provide another good method of determining the end-point energy because, in this method,

$$E_{\text{max}} (\beta^+) = Q - 2.311 \text{ MeV} + (N^1 - n) c^2 - 2m_e c^2$$

and there is only one value, Q, need to be measured. This measurement is relatively simpler than that in ref. 24.
9. States in $^{14}\text{N}$

In addition to the knowledge of $^{14}\text{N}$ collected by Ajzenberg and Lauritsen\textsuperscript{6)} the present work provides the following additional information:

(a) The energies of the states at $E_x = 0$, 2.311, 3.945, 4.91, 5.10, 5.69, 5.83, 6.21, 6.44, and 7.03 MeV are consistent with the experimental results on $^{12}\text{C}(\text{He}^3,p)$ reactions. Although there was no special intention to measure these energies precisely, they were used in the kinematic calculation in the identification of the various proton groups. The agreement between experiments and calculations were good.

(b) There is doubt about the existence of the two states at $E_x = 6.05$ MeV and 6.70 MeV. These two states were suggested by Burge and Prouse\textsuperscript{45)} and Hossain and Kamal\textsuperscript{45)} in their study on $^{14}\text{N}(p,p')$ at one cyclotron energy of 9.5 MeV. The indication of these two levels in their results were very weak peaks in the spectra at certain angles. The resolution used in the measurements of the spectra was not very high. No detailed study of excitation function or angular distribution was made. In the present study of $^{12}\text{C}+\text{He}^3$ reactions these two proton groups did not show up in any of the spectra taken.

(c) The parity of the 6.44 MeV state was determined to be even. Previous reports gave no definite assignment of this parity. From the analyses of elastic $\text{He}^3$, $p$, and the 6.44 MeV gamma rays given above, the assignments of even parity for this state is quite convincing. Determination of this parity has resolved the uncertainty about the configuration of this state in the shell-model calculation of the states
in \( {^4\text{H}} \).

(d) All the states with \( E_x = 4.91, 5.10, 5.69, 5.83, 6.21, \) and 7.03 MeV have parities not yet definitely assigned. It seems possible, in making detail study of the present \( {^{12}\text{C}} + {^3\text{He}} \) reactions, to obtain some of these unknown properties.

10. States in \( {^1\text{O}} \)

For \( {^3\text{He}} \) energies from 1.8 to 5.4 MeV in the \( {^{12}\text{C}} + {^3\text{He}} \) reactions and for proton energies from 6.3 to 12 MeV in \( {^4\text{H}}(p,n){^1\text{H}} \) reaction, the corresponding excitation energy in the compound nucleus \( {^1\text{O}} \) are from 13.51 to 16.39 and from 13.17 to 18.49 MeV. In this excitation energy region of \( {^1\text{O}} \), not much detailed study has been made. Bromley et al. \(^{19} \) and Johnston et al. \(^{20} \) have made some predictions of states from the general examination of the excitation curves and cross sections. Their results were summarized by Ajzenberg and Lauritsen \(^{8} \) and is quoted here in Table 6.

### Table 6

<table>
<thead>
<tr>
<th>( E(\text{He}^3) ) a (MeV)</th>
<th>Resonant for</th>
<th>( E_x ) (MeV)</th>
<th>( J^\pi )</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.15 ( p_0 ) n</td>
<td>13.79</td>
<td>(1/2+)</td>
<td></td>
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<tr>
<td>2.52 ( p_0 p_1 p_2 p_3 ) n</td>
<td>14.09</td>
<td></td>
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<tr>
<td>2.70 ( p_1 p_2 ) n</td>
<td>14.2</td>
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Table 6 (cont'd)

<table>
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<th>14.5</th>
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<td>P₀ P₁ P₂</td>
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<td>3.6</td>
<td>P₀ P₁ P₂</td>
<td>15.0</td>
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<td>4.4</td>
<td>P₀ P₁ P₂</td>
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<td>4.8</td>
<td>P₀ P₁ P₂</td>
<td>15.9</td>
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</table>

a. The first three resonances are primarily from Bromley et al.¹⁹), the last four from Johnston et al.²⁰)

From the present experiments and analyses of the C¹² + He³ reactions and the N¹⁴(p,n)O¹⁴ reaction, more information has been obtained for the nucleus O¹⁵. The summarized resonance parameters from the analyses in the above sections are given in table 7 and table 8.

The calculation of the reduced widths and Wigner limits were from the following relations:

\[ \gamma_{\alpha \ell}^2 = \frac{\Gamma_{\alpha \ell} (\text{c.m.})}{2 \mu \alpha_{\ell}^2} \]

\[ \gamma_{W}^2 = \frac{3 \hbar^2}{2 \mu \alpha_{\ell}^2} \quad \text{if} \quad \frac{\gamma_{\alpha \ell}^2}{\gamma_{W}^2} \leq \sim 0.20 \]

where

\[ P_{\alpha} = \hat{R}_{\alpha} \alpha_{\ell} \]

\[ A_{\alpha \ell}^2 = F_{\alpha \ell}^2 + G_{\alpha \ell}^2 \]

\[ \alpha_{\ell} = \text{interaction radius} \]

\[ \mu = \text{reduced mass of the particles} \]

The formula

\[ \alpha_{\ell} = 1.45 \left( A_1^{1/3} + A_2^{1/3} \right) 10^{-13} \text{ cm} \]

was used for calculating radius. The penetration factors were obtained from references[^31][^6][^7].
Table 7
Resonance parameters of the C^{12}+He^{3} reactions and the H^{14}(p,n)O^{11} reaction

<table>
<thead>
<tr>
<th>E_{He^{3}} (MeV)</th>
<th>Resonant for:</th>
<th>√'lab (MeV)</th>
<th>√'c.m. (MeV)</th>
<th>J^π</th>
<th>E_{X}(O^{15}) (MeV)</th>
<th>√'lab (MeV)</th>
<th>√'c.m. (keV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.45 ± .04</td>
<td>He^{3} p_{1} n</td>
<td>200±20</td>
<td>160±16</td>
<td>1/2^- , 3/2^-</td>
<td>14.03±.03</td>
<td>7.5</td>
<td></td>
</tr>
<tr>
<td>2.75 ± .04</td>
<td>He^{3} p_{1} n</td>
<td>420±40</td>
<td>336±32</td>
<td>1/2^+</td>
<td>14.27±.03</td>
<td>7.7</td>
<td></td>
</tr>
<tr>
<td>2.99 ± .01</td>
<td>He^{3} p_{0} p_{5} p_{9}</td>
<td>125±10</td>
<td>100±8</td>
<td>5/2^+</td>
<td>14.62±.008</td>
<td>7.7</td>
<td></td>
</tr>
<tr>
<td>3.28 ± .04</td>
<td>p_{0}</td>
<td>220±50</td>
<td>176±40</td>
<td></td>
<td>14.69±.03</td>
<td>7.95</td>
<td></td>
</tr>
<tr>
<td>3.60 ± .04</td>
<td>p_{0}</td>
<td>500±30</td>
<td>400±24</td>
<td></td>
<td>14.95±.03</td>
<td>8.20</td>
<td></td>
</tr>
<tr>
<td>4.20 ± .01</td>
<td>He^{3} p_{5} p_{6}</td>
<td>80±15</td>
<td>64±12</td>
<td></td>
<td>15.43±.01</td>
<td>6.05</td>
<td></td>
</tr>
<tr>
<td>4.37 ± .04</td>
<td>p_{1} p_{4} p_{8} p_{9}</td>
<td>100±300</td>
<td>80±24</td>
<td></td>
<td>15.57±.03</td>
<td>6.05</td>
<td></td>
</tr>
<tr>
<td>4.6 ± .1</td>
<td>n</td>
<td>15.75±.08</td>
<td>9.05</td>
<td></td>
<td>16.07±.08</td>
<td>9.4</td>
<td></td>
</tr>
<tr>
<td>5.0 ± .1</td>
<td>He^{3} n</td>
<td>16.48±.05</td>
<td>9.85±.05</td>
<td></td>
<td>16.68±.05</td>
<td>600±100</td>
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</table>


<table>
<thead>
<tr>
<th>$E_x (0^{15})$ (MeV)</th>
<th>$E_{He^3}$ (MeV)</th>
<th>$\Gamma$ (keV)</th>
<th>% error</th>
<th>outgoing</th>
<th>$\Gamma_{He^3}$, $\Gamma_{\beta}$ (keV)</th>
<th>$\Gamma_{\beta}$ (keV)</th>
<th>% error</th>
<th>% error</th>
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<tbody>
<tr>
<td>14.46</td>
<td>2.99</td>
<td>100</td>
<td>8</td>
<td>$He^3$</td>
<td>$0.062$</td>
<td>0.13</td>
<td>11</td>
<td>22</td>
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<tr>
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<td></td>
<td>$0.00512$</td>
<td>0.0341</td>
<td>20</td>
<td>28</td>
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<td></td>
<td>$0.00585$</td>
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<td>28</td>
</tr>
<tr>
<td>14.27</td>
<td>2.75</td>
<td>336</td>
<td>9.5</td>
<td>$He^3$</td>
<td>$0.02823$</td>
<td>0.565</td>
<td>40</td>
<td>49.5</td>
</tr>
<tr>
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<td>$0.04035$</td>
<td>0.807</td>
<td>40</td>
<td>49.5</td>
</tr>
<tr>
<td>14.03</td>
<td>2.45</td>
<td>160</td>
<td>10</td>
<td>$He^3$</td>
<td>$0.01303$</td>
<td>0.1303</td>
<td>30</td>
<td>40</td>
</tr>
<tr>
<td></td>
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<td></td>
<td></td>
<td></td>
<td>$0.01572$</td>
<td>0.1572</td>
<td>30</td>
<td>40</td>
</tr>
<tr>
<td>$E_x^{(0)}$ (MeV)</td>
<td>$E_{He^3}$ (MeV)</td>
<td>$\Gamma$ (keV, c.m.)</td>
<td>Outgoing channel</td>
<td>$\ell'$</td>
<td>Reduced Width $\gamma_{\ell'\ell''}^2$ (keV)</td>
<td>°W.L. °/° error</td>
<td></td>
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<tr>
<td>------------------</td>
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</tr>
<tr>
<td>1.146</td>
<td>2.99</td>
<td>100</td>
<td>He$^3$</td>
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<td>4.63 20</td>
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<td>100</td>
<td>$p_9$</td>
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<td>123.9</td>
<td>4.51 24</td>
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<tr>
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<td>100</td>
<td>$p_1$</td>
<td>2</td>
<td>2.47</td>
<td>0.09 30</td>
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<td>100</td>
<td>$n$</td>
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<td>21.4</td>
<td>0.78 30</td>
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<td>1.144</td>
<td>2.75</td>
<td>336</td>
<td>He$^3$</td>
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<td>15.9</td>
<td>1.77 40</td>
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<td>2.75</td>
<td>336</td>
<td>$p_1$</td>
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<td>2.06 50</td>
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<td>2.75</td>
<td>336</td>
<td>$n$</td>
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<td>5.31 50</td>
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<td>1.1403</td>
<td>2.45</td>
<td>160</td>
<td>He$^3$</td>
<td>1</td>
<td>39.0</td>
<td>4.35 30</td>
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</tr>
<tr>
<td>1.1403</td>
<td>2.45</td>
<td>160</td>
<td>$p_1$</td>
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<td>8.60</td>
<td>0.314 40</td>
<td></td>
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<td>2.45</td>
<td>160</td>
<td>$n$</td>
<td>1</td>
<td>26.5</td>
<td>0.968 40</td>
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</table>
The results are given in table 9.

11. Cluster nature of the nucleus $^0_{15}$

The large cross section of the $p_0$ group at the 2.99 MeV resonance in the $^{12}\text{C}+\text{He}^3$ reactions suggests the cluster nature of the nucleus $^0_{15}$. To make further study on this point, the reduced widths and ratios to Wigner limits of the $p_0$, $p_1$, $n_0$ elastic $\text{He}^3$ were calculated, given in table 9. A comparison of the two-body reduced widths$^{18}$ is listed in table 10.

Table 10

Two body reduced widths of states in $^0_{15}$

<table>
<thead>
<tr>
<th>Ex (MeV)</th>
<th>J T</th>
<th>$\Theta_{2\text{He}^3+\text{C}^{12}}$</th>
<th>$\Theta_{2p_0^+\text{N}^{1h}\ast}$</th>
<th>$\Theta_{2p_1^+\text{N}^{1h}\ast}$</th>
<th>$\Theta_{2n^0\text{N}^{1h}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$1h_46$</td>
<td>$5/2^+$</td>
<td>0</td>
<td>.0463</td>
<td>.0451</td>
<td>.0009</td>
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</table>

$\Theta_{\alpha+\beta}^2 =$ two-body reduced width for the $\alpha+\beta$ pair, expressed as a fraction of the Wigner limit.

From table 10, one can see that the amplitudes for the $p_0^+\text{N}^{1h}\ast$ and $\text{He}^3+\text{C}^{12}$ pairs are relatively larger than other pairs in the two-body channels of the $^{12}\text{C}+\text{He}^3$ reactions at 2.99 MeV (corresponding to $\text{Ex} = 1h_46$ MeV in $^0_{15}$). It should be remarked that the reduced widths of the other outgoing channels were not calculated because of difficulty in analysis. However, the experimental results show that most of these channels do not show resonance structure at 2.99 MeV. One would expect they would not have large reduced widths. But this is not certain for the $\alpha_{0}$ channel, which shows larger yield and resonance phenomenon at 2.99 MeV.
V. CONCLUSION

In conclusion, it would be worthwhile to summarize some main features of the present experiments and analyses. In addition to the previous experiments reported in the literature, the present experiments have studied in some detail the following reactions:

$^{12}$C($^3$He,$^3$He)$^1$H with proton groups to the excited states of $^1$H at 4.91, 5.10, 5.69, 5.83, 6.23, 6.44, and 7.03 MeV ($p_3$, $p_4$, $p_5$, $p_6$, $p_8$, $p_9$, and $p_{11}$); $^{12}$C($^3$He,$\alpha$)$^{11}$C with $\alpha$ groups to the ground state and the first excited state of $^{11}$C for $^3$He energies from 1.8 to 5.4 MeV; the total neutron cross sections of $^{12}$C($^3$He,n)$^{11}$H from threshold (1.445 MeV) to 5.2 MeV; and the total neutron cross sections of $^1$H(p,n)$^{11}$H from threshold (6.335 MeV) to 12 MeV. Together with the analyses that have been made so far, the following few main features are probably worthwhile to mention:

1. States in $^1$H and $^3$H

The presence of the compound nuclear process in the various reactions made some quantitative calculations possible. From these calculations, some consistent parameters for the states of the nuclei $^1$H and $^3$H were obtained. These parameters were summarized in tables 7, 8, 9. The most convincing assignment is that of the parameters for the 2.99 MeV resonance in the $^{12}$He$^3$ reactions with $J^\pi = 5/2^+$ for the 1.46 MeV state of $^3$H and even parity for the 6.4 MeV state of $^1$H.

The energies of the excited states in $^3$H were also obtained, given in table 7. Although there are some discrepancies between the present results and the previous ones (see table 6), it was believed
that the present results should be better because the present results include the analyses of many outgoing channels and in some cases including the total cross sections. Three new states in 0\textsuperscript{15} were observed. The one at Ex = 14.69 MeV was from the total cross sections of C\textsuperscript{12}(He\textsuperscript{3},p\textsubscript{p})N\textsuperscript{11}\textsuperscript{4} and N\textsuperscript{11}\textsuperscript{4}(p,n)O\textsuperscript{11}\textsuperscript{4}. The one at Ex = 15.43 MeV was from the C\textsuperscript{12}(He\textsuperscript{3},p\textsubscript{p})N\textsuperscript{11}\textsuperscript{4*} and C\textsuperscript{12}(He\textsuperscript{3},p\textsubscript{p})N\textsuperscript{11}\textsuperscript{4*} reactions. The one at Ex = 16.48 MeV was from the N\textsuperscript{11}\textsuperscript{4}(p,n)O\textsuperscript{11}\textsuperscript{4} total cross sections. The present experiments indicate that the two possible states at Ex = 6.05 and 6.70 MeV in N\textsuperscript{11}\textsuperscript{4} do not appear in the C\textsuperscript{12}+He\textsuperscript{3} reactions in 1.8 - 5.4 MeV region.

A summary of all the reactions is shown in fig. 36.

2. Reaction mechanism

The present analyses, given in Chapter IV, assumed pure compound nucleus formation. The results for the 2 to 3 MeV regions are reasonably good. So far, the analysis for the reaction channels was carried out only for the single channel spin cases. The evidence of resonance structure in the various reaction channels (c.f. excitation curves and angular distributions of p\textsubscript{p}, p\textsubscript{3}, p\textsubscript{4}, p\textsubscript{5}, p\textsubscript{6}, p\textsubscript{9}, p\textsubscript{11}, \psi\textsubscript{0}, \psi\textsubscript{1}) suggest that an extension of the analysis to reaction channels having two outgoing channel spins may give more insight about the nature of the reactions.

The general feature of the C\textsuperscript{12}+He\textsuperscript{3} reactions is that broad resonances do appear in most of the outgoing channels and for He\textsuperscript{3} energies up to 11 MeV, but most of the resonance positions vary for different channels and for different angles of the same channel. This suggests interference between overlapping resonances in the compound nuclear reactions or interference between different reaction mechanisms.
In order to obtain more conclusive results, further studies, both experimental and theoretical, are required.

3. Proposed further work

The immediate steps for further analysis on the basis of pure compound nucleus theory would be an extension to the reaction channels having two outgoing channel spins. Experimental measurements of the total cross sections of the many outgoing channels are also essential in the analysis. It would be of interest to see how far this kind of analysis could be carried out.

On the other hand, for those channels which present obvious evidence of other reaction mechanisms (e.g. $p_2$ and $p_0$ channels), analysis based on the other assumptions should also be interesting. Also, the connection between the nature of these reactions and the structure of the nucleus should be studied.

The remeasuring of the $^{11}N(p,n)^{11}O$ threshold energy with high precision has its own significance.
Symbols used in the analyses of elastic $\text{He}^3$ and reaction channels.

\[ k = \frac{m_\alpha v_\alpha}{\hbar} \], where \( m_\alpha \) = reduced mass in channel \( \alpha \) and 

\[ v_\alpha \] = relative velocity in channel \( \alpha \).

\[ \eta = \frac{z_1 z_2 e^2}{\hbar v_\alpha} \]

\[ Y^m_\ell(\theta, \phi) \] = normalized spherical harmonics

\[ \sigma_\ell = \text{arg} \Gamma(1 + \ell + \frac{\hbar}{\eta}) \]

\[ \phi_\ell = \sigma_\ell - \sigma_0 = \sum_{s=1}^{2} \tan^{-1} \left( \frac{\eta}{s} \right) \]

\( \phi_\ell \) = hard sphere phase shift = \(-\arctan \left( \frac{E_\ell}{G_\ell} \right)\)

\( \beta^\tau \) = resonant phase shift

\( l(l+1) \) = orbital angular momentum of incident (outgoing) particle

\( \Gamma \) = total width (laboratory) of the state

\( \Gamma_\ell \) = partial width in channel \( \alpha \) with orbital angular momentum \( \ell \)

\( \Gamma^\tau \) = total width (laboratory) of a resonance due to state of \( \bar{J} \pi \)

\( \Gamma^\tau \ell \) = partial width

\( S \) = channel spin in the incident channel

\( S' \) = channel spin in the outgoing channel
PART TWO

States in $\text{H}^{13}$ and $\text{C}^{13}$ From the Reactions

$\text{B}^{10}(\text{He}^3, p \gamma_{15.1}) \text{C}^{12*}$ and $\text{B}^{11}(d, n \gamma_{15.1}) \text{C}^{12*}$
I. INTRODUCTION

It has been demonstrated\(^{49,50}\) that the 15.1-MeV state of \(^{12}\text{C}\) has isotopic spin equal to 1 (\(T = 1\)). In fact, this state is the \(T_z = 0\) member of the isobaric triplet comprising it and the ground states of \(^{12}\text{B}\) and \(^{12}\text{N}\). This state has a high gamma-ray emission width: about 75% of the total width (\(\gamma \gamma = 75\% \pm 20\%\)). The gamma-ray de-excitation of this state is about 97% to the ground state and about 3% to the first excited state. This 15.1 MeV state has sufficient excitation to break up into three alpha particles, either directly or via states in \(^{8}\text{Be}\). However, alpha-particle breakup is forbidden if isotopic spin is conserved. Hence the high gamma-ray emission width implies the effectiveness of the isobaric spin selection rule.

This 15.1-MeV gamma ray has been observed by many groups\(^{1,2}\) in many reactions which lead to the 15.1 MeV state of \(^{12}\text{C}\). The purpose of the present work was to measure the excitation curves of this 15.1 gamma ray in the reactions \(^{10}\text{Be}(^{3}\text{He}, p \gamma )^{12}\text{C}^{\ast}\) (15.1 MeV state) (\(Q = 4.58\) MeV) and \(^{11}(d, n \gamma )^{12}\text{C}^{\ast}\) (\(Q = -1.38\) MeV). From the study of the nature of these excitation curves one would expect to obtain information on the reaction mechanism as well as on nuclear states and structure. It was hoped that the present measurements could provide some information in this respect.

The present two reactions were measured together with the 15.1 MeV gamma ray from the \(^{13}(^{3}\text{He}, \alpha \gamma )^{12}\text{C}^{\ast}\) reactions\(^{51}\).
II. EXPERIMENTAL METHODS

The experiments were performed using the Rice University 5.5 MeV Van de Graaff accelerator. The details of the experimental methods are described in the following separate sections.

1. Targets

The B\textsuperscript{10} target used was made by evaporating 96% enriched B\textsuperscript{10} on to a 0.01" tungsten blank. Its thickness was determined by running through the 1.518 MeV resonance (\( \gamma \) c.m. = 1.4 ± 4 keV) of the B\textsuperscript{10}(\( \alpha \),n)\textsuperscript{13} reaction\textsuperscript{8}) using a modified long counter (BF\textsubscript{3} proportional counter embedded in a paraffin cylinder). The B\textsuperscript{11}(\( \alpha \),n)\textsuperscript{14} 2.06 MeV resonance (\( \gamma \) in = 66 keV) was also measured for comparison. This is possible because there is about 4% B\textsuperscript{11} in the target. The results agree very well. The thickness was about 45 ± 4 keV for 1.52 MeV \( \alpha \)-particles, or about 20 keV for 3 MeV He\textsuperscript{3} particles.

The B\textsuperscript{11} target used was made by evaporating 96% enriched B\textsuperscript{11} on to a 0.01" tungsten blank. The thickness was determined by running through the B\textsuperscript{11}(\( \alpha \),n)\textsuperscript{14} 2.06 MeV resonance using the same experimental arrangement used for B\textsuperscript{10} target thickness measurements. The thickness was about 95 keV for 2.1 MeV \( \alpha \)-particles or about 12 keV for 3 MeV deuterons.

2. Gamma-ray detection

A 2 inch by 2 inch NaI crystal was used for the measurement of the excitation curves, and a 1 inch by 1 inch NaI crystal for the angular distribution measurements. The electronic arrangement similar to that used in the experiments on gamma rays from C\textsuperscript{12} He\textsuperscript{3} (cf. fig. 4) was used
to set the window of the single-channel analyzer scaler, namely, to set
the upper and lower limits of the window by direct observation of the
spectrum displayed on 256-channel analyzer. The data for all excitation
curves were taken by feeding the signal in parallel to the single
channel analyzer as well as to the 256-channel analyzer so that one
could check the constancy of the gain and could check a few points on
the single channel excitation curve by measuring the area on the
spectrum from the tape records from the 256-channel analyzer.

Because the 15.1 MeV gamma ray has lower yields compared with the
low energy gamma rays, the possibility of "pile-up" has to be avoided.
To do this, the beam was kept low throughout the experiment. The
effect of "pile-up" was checked by watching the shape of the spectrum
on 256-channel analyzer. To ensure the results, a tunnel diode dis-
riminator and linear gating preamplifier, designed by Rabson\textsuperscript{52}) was
also used to check the results. They agreed very well. This preampli-
 fier could exclude the low energy pulses by adjusting a discriminator.
Only those pulses which were above the discriminating voltage triggered
the gating circuit and were driven to the amplifier. Therefore, the
number of pulses going into the amplifier was considerably reduced and
thus the "pile-up" effect. This special preamplifier was also used by
Perry \textit{et al.}\textsuperscript{53}) in their study of Li\textsuperscript{7}(p,\gamma)Be\textsuperscript{8}.

The counter was put at 0° to the beam and was very close to the
target for the excitation curve measurements. For angular distribution
measurements the distance between the front surface of the 1 inch by 1
inch NaI crystal to the target was about 13.6 cms.
3. Identification of the 15.1 MeV gamma ray

The reaction $B^{11}(p,\gamma)C^{12}$ was used in identifying the 15.1 MeV gamma ray. This reaction yields two high energy gamma rays\(^8\) with energies $E_1 = (15.956 + 11/12 E_{\text{bind.}})$ MeV and $E_2 = (E_1 - 4.43)$ MeV, and a 4.43 MeV gamma ray. The method used in identifying the gamma rays was to keep the detector condition constant. Only the targets and beams were changed. The spectra obtained by this method for the reactions $B^{10}(He^3,p)^{12}(He^3,\gamma)_1$, $B^{11}(d,n)^{12}C^{12}$, $C^{13}(He^3,\alpha)^{12}(He^3,\gamma)_1$, and $B^{11}(p,\gamma)^{12}C^{12}$ are shown in fig. 37. The spectrum from $B^{10}He^3$ shows mainly the 4.43 MeV and the 15.1 MeV gamma rays from $B^{10}(He^3,p)$ reaction. The spectrum from $B^{11}d$ shows the 15.1 and 4.43 MeV gamma rays from $B^{11}(d,n)$ reaction and a smoothly rising low energy background from the neutron capture gamma rays in the NaI crystal. For the spectrum from $C^{13}He^3$, in addition to the 15.1 MeV gamma ray from $C^{13}(He^3,\alpha)^{12}(He^3,\gamma)_1$, there are many other low energy gamma rays from the various $He^3$ induced reactions on $C^{13}$ and $C^{12}$. To ensure that the spectra obtained from the 256-channel analyzer had no distortion from "pile-up" effect, the same spectra were measured by a single channel analyzer and scaler of which the "pile-up" effect is not so serious as for the 256. The beam condition was kept about the same. The results agreed very well.

The window settings for the measurements of the excitation curves are shown on each spectrum in fig. 37.

4. Estimate of cross sections

The estimate of the absolute cross sections was done in the following manner. The detector was put at a known distance from the
target (7 cm\textsuperscript{s} in the $^{11}\text{B}(d,n)^{12}\text{C}^{*}$ reaction and 1 cm in the $^{10}\text{B}(\text{He}^{3},p)^{12}\text{C}^{*}$ reaction). Spectra were taken, with low beam current, at a few bombarding energies. By comparing spectra from these two reactions and the $^{11}\text{B}(p,\gamma)^{12}\text{C}$ reaction one could have a rough idea of the shape of the 15.1 MeV gamma-ray spectrum for the same crystal. The area of the spectra was then measured. Then the absolute cross sections were calculated using the measured target thickness and the efficiency curve of the NaI crystal\textsuperscript{55}). The overall uncertainty for the final value of the cross sections was about 50%.
Figure Captions

Fig. 37. Gamma-ray spectra from the $^10_7$He$^3$, $^11_7$He$^3$, $^11_4$He$^3$, and $^11_8$He$^3$ reactions. The gamma-ray energy scale was determined from the known energies of gamma rays from $^11_8$He$^3$. The windows used in taking the 15.1 MeV gamma-ray excitation curves are shown.

Fig. 38. 15.1 and 4.43 MeV gamma-ray yield at 0° from $^10_7$(He$^3$,pγ)C$^{12*}$. As the counter was very close to the target, the 90° yield had essentially the same shape as the 0° ones. The angular distributions taken at 2.9 and 4.0 MeV were essentially isotropic. The shape of the yield curves shown here should be similar to that of the total yield. The solid lines were drawn through the data points. The arrows marked the approximate positions of the resonances.

Fig. 39. Yield of the 15.1 MeV gamma ray at 0° from $^11_8$(d,nγ)$^{15,1}$C$^{12*}$. The solid line was drawn through the data points. The parameters for the resonances are given in table 11.

Fig. 40. Comparison of the two reactions $^10_7$(He$^3$,pγ)$^{15,1}$C$^{12*}$ and $^11_8$(d,nγ)$^{15,1}$C$^{12*}$, with a level diagram of the states of the compound nuclei C$^{13}$ and N$^{13}$ in the energy ranges of the excitation curves. The resonance parameters were summarized in table 12.
\( \gamma \)-RAY SPECTRA FROM THE VARIOUS REACTIONS \((2'' \times 2'' \text{ NaI})\)

\[ E_{\text{He}^3} = 1.80 \text{ MEV} \]

\[ E_d = 3.08 \text{ MEV} \]

\[ E_{\text{He}^3} = 3.63 \text{ MEV} \]

\[ E_{\text{p}} = 1.65 \text{ MEV} \]

\[ E_{\text{p}} = 17.46 \text{ MEV} \]
15.1- AND 4.43-Mev $\gamma$-RAY YIELDS FROM $^{10}\text{Be}^3(\text{He}^3, p\gamma)C^{12*}$

Measured at $0^\circ$

$\gamma_{15.1}$

$\gamma_{4.43}$

$\times \frac{1}{50}$

Target Thickness:

$\sim 20$ keV at $E_{\text{He}^3} = 3.0$ MeV
YIELD OF 15.1 Mev $\gamma$-RAYS FROM $B^{11}(d, n\gamma)C^{12,*}$
Measured at 0°

Target Thickness: $\sim$ 12 keV at $E_d = 3.0$ Mev
III. EXPERIMENTAL RESULTS

1. 15.1 MeV gamma ray from $^1\text{He}^3 (\text{He}^3, p \gamma)^{12\ast}_{15.1}$

The 15.1- and 4.43- MeV gamma-ray excitation curves at 0° from 1.8 to 5.5 MeV of the reaction $^1\text{He}^3 (\text{He}^3, p \gamma)^{12\ast}$ are shown in fig. 38. The solid lines were drawn through the data points. Because the counter was put very close to the target, the shape of the curves should be similar to that of the total cross sections. In fact, two angular distributions taken at 2.9 and 4.0 MeV were essentially isotropic. The 90° excitation curve was also measured. It has the same shape as the 0° one. Thus the lines in fig. 37 have the shapes of the total cross sections.

The 4.43 MeV gamma-ray excitation curve rises smoothly from 1.6 to 5.5 MeV, while the 15.1 MeV gamma-ray excitation curve rises from 1.8 to about 4 MeV and then stays flat up to 5.5 MeV with indications of resonance structure at 2.85 and 5.2 MeV. After drawing a smooth line and subtracting out the continuous yield represented by this curve from the data points, the resonance parameters for these two resonances are:

\[ \Delta E = 2.85 \pm 0.05 \text{ MeV}, \quad \Gamma^\prime_{\text{lab}} = 450 \pm 50 \text{ keV}; \quad E = 5.2 \pm 0.1 \text{ MeV}, \]

\[ \Gamma^\prime_{\text{lab}} = 240 \pm 80 \text{ keV}. \]

This reaction has also been studied by Almqvist et al. 50) in the 1.0 to 2.6 MeV region. In the overlapping region, their results agree with the present results. They obtained a total cross section of the 15.1 MeV gamma ray of $0.60 \pm 0.01$ mb at 2.0 MeV $\text{He}^3$ energy, assuming an isotropic angular distribution. From the present data, the total cross section is about 0.53 mb at 2.0 MeV. Within experimental uncertainty,
it agrees with theirs.

2. 15.1 MeV gamma ray from B^{11}(d,n)_{15.1}C^{12*}

The 15.1 MeV gamma-ray excitation curve at $0^\circ$ from threshold (1.633 MeV) to 5.5 MeV of the reaction B^{11}(d,n)_{15.1}C^{12*} (15.1 MeV state) is shown in fig. 39. Most of the data were averages of 4 to 5 runs. The solid line was drawn through the data points. The yield rises smoothly from threshold to about 2.5 MeV, then decreases gradually to 5.5 MeV with indication of resonances at 2.18, 3.08, 3.71, and 4.41 MeV. The resonance parameters for these resonances were obtained by subtracting out the yield represented by a continuous smooth curve. The results along with the previous report^{49)} are given in table 11.

Table 11

Resonance parameters from B^{11}(d,n)_{15.1}C^{12*} (15.1 MeV state)

<table>
<thead>
<tr>
<th>Present Results</th>
<th>Kavanagh and Barnes$^a$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$E_d$ (MeV)</td>
<td>$\sqrt{\gamma}$ (keV)</td>
</tr>
<tr>
<td>$\sqrt{\gamma}$ (keV)</td>
<td>$\sqrt{\gamma}$ (keV)</td>
</tr>
<tr>
<td>-----------------</td>
<td>------------------------</td>
</tr>
<tr>
<td>2.18$\pm$.02</td>
<td>140$\pm$20</td>
</tr>
<tr>
<td>3.08$\pm$.02</td>
<td>185$\pm$20</td>
</tr>
<tr>
<td>3.71$\pm$.02</td>
<td>170$\pm$25</td>
</tr>
<tr>
<td>4.41</td>
<td>Broad</td>
</tr>
</tbody>
</table>

$^a$R. W. Kavanagh, C. A. Barnes, Phys. Rev. 112, 503 (1958) (ref. 49)

This reaction has been studied by Kavanagh and Barnes^{49)} in the
1.6 - 3.25 MeV region. They have reported the threshold at 1.633 ± 0.003 MeV using Li\textsuperscript{7}(p,n) threshold (taken as 1881 ± 1 keV) as calibration reference. Their estimated cross section was 29 ± 7 mb at 2.2 MeV. The cross section obtained from present result at 2.2 MeV is about 23 ± 11 mb.

The angular distribution at 4.8 MeV was checked in the present experiment. The anisotropy was less than 10%.
IV. DISCUSSION OF RESULTS

1. States in the isobaric compound nuclei \( C^{13} \) and \( N^{13} \)

For \( B^{10}(He^{3},p\gamma_{15.1}) \) from 1.8 to 5.5 MeV, the corresponding excitation energy in the compound nucleus \( N^{13} \) is from 23.02 to 25.87 MeV. For \( B^{11}(d,n\gamma_{15.1}) \) from 1.6 to 5.5 MeV, the corresponding excitation energy in \( C^{13} \) is from 20.02 to 23.33 MeV. These two regions are very close to each other. A comparison of the above two reactions and of the level diagrams of the compound nuclei \( C^{13} \) and \( N^{13} \) is shown in Fig. 40. In addition to the previously reported energy levels\(^{49,56}\), the levels observed in the present measurements are also shown in the figure. It is of interest to note that the level densities in the corresponding regions of \( C^{13} \) and \( N^{13} \) are about the same. The resonances observed in the range of bombarding energies of the present experiment are listed in Table 12.

### Table 12

<table>
<thead>
<tr>
<th>Target nucleus</th>
<th>Incident particle</th>
<th>Resonance energy (MeV)</th>
<th>Resonance width (MeV)</th>
<th>Compound nucleus</th>
<th>Energy of excitation of compound nucleus</th>
</tr>
</thead>
<tbody>
<tr>
<td>( B^{10} )</td>
<td>( He^{3} )</td>
<td>2.0(^{a})</td>
<td>.5</td>
<td>( N^{13} )</td>
<td>23.2</td>
</tr>
<tr>
<td></td>
<td></td>
<td>2.85( \pm .05 )</td>
<td>.45 ( \pm .05 )</td>
<td></td>
<td>23.8</td>
</tr>
<tr>
<td></td>
<td></td>
<td>3.7(^{a})</td>
<td>.7</td>
<td></td>
<td>24.5</td>
</tr>
<tr>
<td></td>
<td></td>
<td>4.1(^{a})</td>
<td>.12</td>
<td></td>
<td>24.8</td>
</tr>
<tr>
<td></td>
<td></td>
<td>4.6(^{a})</td>
<td>.15</td>
<td></td>
<td>25.2</td>
</tr>
<tr>
<td></td>
<td></td>
<td>5.2 ( \pm .1 )</td>
<td>.24 ( \pm .08 )</td>
<td></td>
<td>25.6</td>
</tr>
</tbody>
</table>
Table 12 (cont'd)

<table>
<thead>
<tr>
<th>B$^{11}$</th>
<th>d</th>
<th>2.18±.010$^b$</th>
<th>0.115±.001</th>
<th>C$^{13}$</th>
<th>20.52</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>3.080±.015$^b$</td>
<td>0.160±.015</td>
<td></td>
<td>21.28</td>
</tr>
<tr>
<td></td>
<td></td>
<td>3.71±.02</td>
<td>0.14±0.21</td>
<td></td>
<td>21.81</td>
</tr>
<tr>
<td>4.41</td>
<td></td>
<td>broad</td>
<td></td>
<td></td>
<td>22.41</td>
</tr>
</tbody>
</table>

$^a$J. P. Schiffer et al., Phys. Rev. 104, 1064 (1956) (ref. 56)
$^b$R. W. Kavanagh, C. A. Barnes, Phys. Rev. 112, 503 (1958) (ref. 49)

2. Reaction mechanism

The B$^{10}$(He$^3$,p) reactions have been studied by Schiffer et al.$^{56}$ for proton groups to the ground state and first excited state of C$^{12}$. They reported the resonances labeled "a" in table 12 (cf. also fig. 40). They were interested in comparing reactions having known transformation of angular momenta to study the reaction mechanism. They concluded that the reactions must proceed, at least in part, by way of compound system. In the present B$^{10}$(He$^3$,p 15,1), the smoothly rising excitation curve with only broad and weak resonance structure does show some similarity to the results of Schiffer et al., for the p$_0$ and p$_1$ groups. The results probably indicate that both compound nucleus formation and direct interaction play important roles in the reaction. The fact that broad resonances appear at different positions for different outgoing channels (p$_0$, p$_1$, and proton to the 15.1 MeV state of C$^{12}$), and for different angles of one outgoing channel (see data on p$_0$ and p$_1$ in ref. 56) suggests the similarity between the (He$^3$,p) reactions on B$^{10}$ and the (He$^3$,p) reactions on C$^{12}$. 
The reactions $^B_{11}(d,n)$ are most likely to be of stripping type, although there is no report on neutrons to the 15.1 MeV state of $^{C_{12}}$ for comparison. The neutron groups to the ground state and first excited state of $^{C_{12}}$ have been reported$^{57,58}$ to proceed mainly via direct or exchange stripping. But the presence of resonance structure in the present results does indicate the probable formation of the compound nucleus system.

3. Conclusion

The present measurements of the 15.1 MeV gamma-ray excitation curves indicate the existence of some new levels in the nuclei $^{C_{13}}$ and $^{B_{13}}$. But they also bring out the problem of explaining the reaction mechanism.
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