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INVESTIGATION OF HIGHLY POPULATED LEVELS OF THE \((d_{5/2})^2\) AND \((f_{7/2})^2\) CONFIGURATIONS BY THE \((\alpha, d)\) REACTION

Ernest Jean-Marie Rivet

(Ph. D. Thesis)

March 24, 1964
INVESTIGATION OF HIGHLY POPULATED LEVELS OF THE \( (d_{5/2})_2 \) AND \( (f_{7/2})_2 \) CONFIGURATIONS BY THE \((\alpha, d)\) REACTION

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INVESTIGATION OF HIGHLY POPULATED LEVELS OF THE \( (d_{5/2}^2) \) AND \( (f_{7/2}^2) \) CONFIGURATIONS BY THE \((\alpha, d)\) REACTION

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ABSTRACT

The \((\alpha, d)\) reaction was observed on \(^{12}C\), \(^{14}N\), \(^{15}O\), \(^{16}Ne\), \(^{20}Ne\), \(^{24}Mg\), \(^{32}S\), \(^{40}Ar\) and \(^{40}Ca\). This reaction was induced by the 48-MeV \(\alpha\)-particle beam of the William H. Crocker Radiation Laboratory's 60-inch cyclotron, and by the 45- and 50-MeV beams of the new 88-inch variable-energy cyclotron. All the deuteron-energy spectra obtained were dominated by one or more highly populated states called the "gross structure" levels. Evidence that these levels have a common configuration is obtained from (a) the remarkable similarity of their angular distributions, and (b) the relationship between their \(Q\) values of formation and the atomic-mass number of the recoil nuclei.

In the assumption of a direct interaction, it is proposed that the levels preferentially populated are of the \(\left[ J_T + (J_p J_n) J' \right] J \) configuration, where the proton and the neutron couple their spin to \(J'\), which in turn couples with the angular momentum of the target to give the final state \(J\). It is also shown that the proton-neutron pair is captured in the \(d_{5/2}\) or \(f_{7/2}\) shell of the recoil nucleus investigated, and that the maximum final spin (5 or 7) is favored.

The \((\text{He}^{3}, p)\) reaction was observed on \(^{12}C\) and \(^{16}O\), and, as expected, the levels highly populated in the \((\alpha, d)\) reactions were once again preferentially populated. The scattering of \(\alpha\) particles from \(^{14}N\) and \(^{16}O\) was also investigated to confirm the two-nucleon nature of the highly populated levels formed by two-nucleon transfer reactions.

The monotonically decreasing pattern of the angular distributions of these gross-structure levels is explained in terms of increasing momentum mismatch.
I. INTRODUCTION

Two types of information can be obtained from the study of nuclear reactions: (a) information concerning general properties of nuclear matter, and (b) spectroscopic information concerning the nuclear structure of a particular level. To fall in the latter category, the observation must be directly interpretable in terms of the properties of the initial and final states involved. Nuclear reactions, in which the incoming light particle is stripped of one or two of its nucleons and the lighter particle observed, constitute an excellent tool to provide spectroscopic information.

Single-nucleon stripping reactions have been widely investigated (see Ref. 3 and references therein), and were very successful in angular momentum and parity assignments to single-nucleon levels. Two-nucleon-transfer reactions are also valuable, since they can reach additional states that could not be formed by single-nucleon-transfer reactions. The capture of two nucleons was first investigated by the \((\text{He}^3, \text{p})\) reaction (usually at low bombarding energies), and in no cases were levels higher than a few MeV studied. The \((\alpha, \text{d})\) reaction has seldom been observed.

The purpose of the present investigation was to study the selectivity of the levels populated by the \((\alpha, \text{d})\) reaction.

The direct-stripping mechanism assumes that the target core is unchanged during the transition and thus the levels that correspond to a proton-neutron pair coupled to the target core will be preferentially populated. Further selectivity of the \((\alpha, \text{d})\) reaction arises from the fact that the wave function of the neutron-proton pair in the captured state must have a high degree of similarity with the wave function of a deuteron in the \(\alpha\) particle.

An earlier \((\alpha, \text{d})\) investigation on \(^{12}\text{C}, ^{14}\text{N}, \text{and} ^{15}\text{N}\) indicated that the deuteron-energy spectra were dominated by highly populated
levels; this preferential population was unexplained. In order to investigate these "gross structure" levels over a wide spread of mass number, the (α, d) reaction was observed on the C\textsuperscript{12}, O\textsuperscript{16}, Ne\textsuperscript{20}, Mg\textsuperscript{24}, S\textsuperscript{32}, Ar\textsuperscript{40}, and Ca\textsuperscript{40} nuclei.

The angular distributions of the preferentially populated states were measured to determine if they exhibited a similar shape, indicative of an identical mechanism of formation. The Q values of formation of these levels are also of interest, since levels of identical configuration should lie nearer the ground state when this configuration approaches the most stable state of the recoil nucleus. This information, together with a few available known angular momentum and parity assignments, is considered in order to identify this preferential population in terms of shell-model configurations.

The (He\textsuperscript{3}, p) reaction, which should populate the same levels, was observed on C\textsuperscript{12} and O\textsuperscript{16} target nuclei. The scattering of α particles from N\textsuperscript{14} and O\textsuperscript{16} was also investigated in an attempt to confirm the two-nucleon nature of the levels highly populated in the (α, d) and (He\textsuperscript{3}, p) reactions.
II. EXPERIMENTAL PROCEDURES

This work was performed with three different accelerators: the Crocker Laboratory's 60-inch cyclotron, the heavy-ion accelerator, and the "new" 88-inch spiral-ridge cyclotron. After a separate description of each of these machines and their respective cave equipment, a section is devoted to a general discussion of the detectors and the electronics used in these experimental measurements. Finally, following a few words about target preparation, the data collection and reduction techniques are discussed in detail.

A. Machines and Cave Equipment

1. The 60-Inch Cyclotron

The experimental facilities of the Crocker Radiation Laboratory's 60-inch cyclotron have already been described elsewhere. This machine provided the helium ions used to induce the reactions reported here at a bombarding energy of ~48 MeV.

Starting from the exit port of the tank, the beam was brought out through a long iron pipe, focused by a quadrupole magnet, and directed by a steering magnet through a collimation system into the scattering chamber. This arrangement is shown in Fig. 1.

The beam was then collected in the Faraday cup and integrated. A system of two remotely controlled 12-position foil wheels, located in front of the magnet protected Faraday cup and containing the proper thicknesses of Al absorbers, was used to determine the range corresponding to one-half the maximum beam intensity. The beam energy was then obtained from helium ion range-energy tables based on experimental proton range-energy data.

The scattering chamber consisted essentially of a 36-in.-diameter vacuum tank provided with a remotely controlled table and target holder. The table could be rotated to any desired angle but
Fig. 1. Experimental arrangement at the 60-inch cyclotron: A, iron pipe; B, adjustable slit; C, quadrupole focusing magnet; D, cyclotron vault; E, shielding wall; F, steering magnet; G, 3/16-inch diameter graphite collimator; H, 3/16-inch diameter tantalum baffle collimator; I, 36-inch scattering chamber; J, target; K, counter telescope and foil wheel; L, monitor; M, foil wheel for measuring beam energy; and N, Faraday cup.
the angle of experimental observation $\theta_L$ was limited to $6^\circ < \theta_L < 174^\circ$ since the edges of the detector holder had to avoid intercepting the beam. The target holder could be retracted completely in a vacuum-tight compartment mounted on the lid of the chamber. The entire system was evacuated by a local pumping unit, which consisted of a 6-inch water-cooled oil-diffusion pump backed by a Kinney mechanical pump.

The counter holder was attached to the rotating table. A remotely controlled 12-position foil wheel, containing various thicknesses of Al absorber and a Th $^{228}\alpha$ source, was mounted immediately in front of the detector. The absorbers were useful for energy calibration of the electronics whereas the radioactive source was there for checking counters.

An especially thin collimated window located at a fixed angle (approx $20^\circ$), was sometimes used to allow a detector outside the chamber to monitor the target thickness during a measurement. When this device was used, the monitor counter consisted of a CsI(Tl) crystal mounted in front of a photomultiplier tube.

2. The Heavy-Ion Linear Accelerator

The $^{12}$C($^{3}$He, $^p$)$^{14}$N and $^{16}$O($^{3}$He, $^p$)$^{18}$F reactions were studied using the 31.2-MeV $^{3}$He beam of the Berkeley heavy-ion linear accelerator (Hilac). The $^{3}$He ions could be accelerated in a +1 or +2 charge state, but a more intense beam was available with the +1 ions. The gas supplied to the ion source of the machine consisted of approximately 2 to 4% $^{3}$He in $^4$He. With this dilution the beam was adequate and the consumption of $^{3}$He gas relatively low. The Hilac and its various components have been previously described by Hubbard and others. 14

As shown in Fig. 2, the beam was brought through a quadrupole magnet, a steering magnet, and two 0.125-in.-diameter tantalum collimators into a 10-in.-diameter scattering chamber. The target was placed at the center of the chamber and the scattered particles
Fig. 2. Experimental arrangement at the Heavy Ion Linear Accelerator: A, 1/8-inch diameter tantalum collimator; B, 0.002-inch thick Mylar window; C, counter arm; D, Faraday cup; E, target holder.
observed through a 0.002-in.-thick Mylar window. This transparent window was so arranged that it was possible to cover a range of 15° to 170° with the Faraday cup attached to the chamber. Small-angle measurements from 0° to 15° were made possible by replacing the Faraday cup by a flange with an aluminium window 0.001-inch thick. The beam intensity was then monitored with a counter mounted at a fixed angle (14°) underneath the chamber. After passing through the window, the scattered particles were detected by a counter telescope located in the atmosphere.

The Hilac is a pulsed-beam machine providing a 2-msec pulse 15 times per second and the beam intensity has to be kept low to avoid bunching the particles in the detectors. It was therefore necessary to use two counting systems in order to increase the efficiency of the operation. As there is no remote control on this scattering chamber, all changes of targets or of counting angles had to be made by hand. The same chamber has been described previously by Alster. 15

3. The 88-Inch Cyclotron

The most recent of the Berkeley accelerators, the 88-inch cyclotron, provided the helium ions to induce the reactions studied at 45 and 50 MeV and some of the scattering experiments reported in this work. *

The 88-inch cyclotron is a variable-energy machine capable of producing a beam of helium ions up to 130-MeV. Figure 3 shows the beam-optics system. In the vertical plane the beam was kept approximately parallel and its height was usually limited to 1 inch by means of a graphite plate placed at the entrance to the analyzer magnet. In the radial plane the first quadrupole-lens doublet from the tank created

* These values for the beam energy were obtained from magnet settings; they were later found to be accurate only to ±2 MeV. 16
Fig. 3. Experimental arrangement at the 88-inch cyclotron.
an image of the cyclotron's effective source about halfway between the quadrupole lens and the analyzing magnet. The analyzing magnet then deflected the beam through 57 deg and threw a radial image on the analyzer slit.

The water-cooled tantalum jaws of the analyzer slit could be opened or closed and the whole assembly could be moved to any radial position in the beam pipe; both operations were performed by remote control. The jaws were set 0.060 in. apart during most of the experimental measurements. After the slit, the beam passed through the main shielding wall of the cyclotron vault. The particles were refocused by a second quadrupole doublet to a radial focus at the target position in the center of the scattering chamber. A vertical collimating slit and antiscattering slit were placed in the beam pipe at a distance of 22 inches from the target. The tantalum slit had an opening of about 0.080 in. wide by 0.50 in. high for most of the measurements.

The scattering chamber and the Faraday cup are described in Sec. A.1. Only one modification was made after moving the chamber from Crocker Laboratory to Bldg 88; the port used to monitor the target through a thin aluminum window was modified into a vacuum-tight isolated compartment. A movable thorium source was mounted in this compartment for counter-testing purposes.

Despite the tight collimation of the optical system, the beam current available in the Faraday cup was typically 0.5 μA. The extracting efficiency of the machine itself was at times as high as 50%.

B. Detectors and Electronics

1. Solid-State Detectors

Since many different solid-state detectors were used in the course of this work, a general discussion of these junctions is appropriate at this point. As each reaction is discussed individually, the characteristics of the particular detectors are mentioned.
In principle, a solid-state detector is a very simple device; it consists essentially of a sensitive region where the particle is stopped and from where the charges caused by the electron-hole formation can be collected in a minimum amount of time.

In the case of the p-n junctions used for part of this work, the sensitive region was obtained by applying a reverse voltage to the junction, thus creating a depletion layer of high resistivity. The junction itself was obtained by diffusing an n-type material (phosphorus) into a p-type (boron-doped) silicon crystal. Figure 4 (a) shows what occurs when a p region comes in contact with a layer of n material. The electrons from the n side will combine with the holes of the p side, thus creating an intrinsic region and building a small internal field. When reverse voltage is applied (positive to the n side and negative to the p side), the electrons and holes are drawn more and more towards the surface and a thicker depletion layer is then created, as shown in Fig. 4 (b).

The depletion-layer thickness follows the relation

\[ W \propto (\rho V)^{1/2} \]

where \( \rho \) is the resistivity of the silicon crystal and \( V \) is the reverse bias voltage. The maximum voltage that can be applied to the junction depends on several variables. Avalanche breakdown in the material or the junction may be the limiting factor, or in other circumstances noise due to surface or bulk-leakage currents may set the limit.\(^1\) It is then obvious that high-resistivity material is required to obtain a thick depletion layer at a reasonable bias voltage; however material exhibiting greater than 10,000-(ohm-cm) resistivity is difficult to obtain and undergoes basic changes during high-temperature processing.\(^2\) One is therefore limited in trying to obtain a thick depletion layer from these p-n junctions and they were used as transmission counters.
Fig. 4. The p-n junction; (a) no bias voltage is applied; (b) bias voltage creates a region of intrinsic conductivity.
Impurity compensation offers the possibility of obtaining thick intrinsic region starting from lower resistivity material; these compensated p-i-n junctions are referred to as Li-drifted detectors. The preparation of these junctions has been described by Elliott. The starting material was again a p-type silicon crystal into which the donor substance, lithium, was thermally diffused. After diffusion the junction was located about 0.020 inch from the lithium side. Figure 5 (a) shows a donor-acceptor profile after diffusion. Then at a temperature of about 125° C, the Li ions were allowed to drift under the influence of a reverse bias, thus forming a compensated region of intrinsic resistivity, as shown in Fig. 5 (b). The ion-drift principle has been described by Pell.

The reverse bias still has the effect of increasing the depth of the intrinsic region, but the resistivity of the compensated silicon is so high (of the order of 200,000 ohm-cm) that only a small bias is required to deplete the whole crystal. In practice, however, biases of a few hundred volts are required to ensure rapid collection of all the charge. During this work, Li-drifted detectors as thick as 0.150 inch were successfully used.

2. Scintillation Counters

One of the two counting systems used at the Hilac consisted of scintillation counters. The transmission detector was a CsI(Tl) crystal 0.012-in.-thick mounted in front of a photomultiplier tube (Dumont 6292) operated at approximately 1100 V. The stopping detector consisted of a NaI(Tl) crystal 0.5 in.-thick monitored by a photomultiplier tube (Dumont 6292) operated at 650 V.

3. Particle Identification

When a target is exposed to the beam, particles of different charges and masses are produced; they all reach the detectors with various amounts of energy depending on the levels formed in the recoil.
Fig. 5. Distribution of lithium atoms ($N_D$) and boron atoms ($N_A$); (a) after the diffusion of the lithium impurity; (b) after the drifting of the lithium.
nucleus. In order to look at a given reaction, one has to be able to sort out a given type of particle, discriminating completely against the others.

For the \(^3\text{He}^\rightarrow\text{p}\) reactions reported in this work, the protons could be sorted out by using an absorber thick enough to eliminate the shorter range particles. This system was adequate since the solid-state counter was not thick enough to stop the outgoing protons and considerable absorber had to be used to degrade the proton energy to within the operating range of the detector.

For the \((\alpha, \text{d})\) reactions, the particles were identified electronically by a device called the multiplier. A similar device was used first by Stokes,\(^{21}\) and its electronic circuitry was described at length by Briscoe.\(^{22}\) The principle of operation of the multiplier arises from the approximate nonrelativistic relationship for the rate of energy loss of charged particles as they pass through matter. This relationship can be stated as

\[
\frac{dE}{dx} = \frac{C_1 M_1 Z_1^2}{E} \ln \frac{E}{C_2 M_1} 
\]

where \(M_1, Z_1,\) and \(E\) are the mass, charge and energy of the particle, and \(C_1\) and \(C_2\) are products of constants. It is seen then that if a pulse proportional to \(dE/dx\) coming from a transmission counter is electronically multiplied by a corresponding pulse proportional to \(E\) from an absorption detector, the product will be proportional to the mass of the counted particle times the square of its charge.

This last statement is true over a wide range of energy if the \(E\) pulse has been corrected by two additional factors. First, it has been shown that the addition of a properly selected constant \(E_0\) to the energy deposited by the particle in the absorption detector will partially compensate for the logarithmic factor in the above equation.\(^{21}\) Second, since the measurement of \(dE/dx\) in practice requires a
finite-energy loss, \( \Delta E \), it is also necessary to add to the measured energy \( E \) a certain amount of the \( \Delta E \) as \( K\Delta E \) in order that \( E \) and \( \Delta E \) may correspond to the same particle energy. A final expression would then be

\[
(E + E_0 + K\Delta E)\Delta E \propto MZ^2
\]

The multiplication of the \( E \) and \( \Delta E \) pulses that are fed into the particle identifier is accomplished electronically by utilizing the relation

\[
(A + B)^2 - (A - B)^2 = 4AB,
\]

where \( A = E + E_0 + K\Delta E \) and \( B = \Delta E \).

The squaring is performed by two square-law tubes (Raytheon QK-329).

Under experimental operations, \( K \) and \( E_0 \) were left as adjustable parameters to permit optimum separation of the different groups of particles. It is also noteworthy that the possibility of producing spurious output pulses arising from the product \( E_0 \) and \( E \) was eliminated in the multiplier-output spectrum by requiring a coincidence between an \( E \) pulse and this output pulse. Figure 6 shows the multiplier spectrum obtained from the bombardment of \( C^{12} \) with 50-MeV alphas.

4. Amplification of the Detector Signal

The signal coming from the detector was preamplified immediately in the cave before being sent to the counting area where it was amplified. The system used in the early part of this work consisted of a low-noise preamplifier \(^{17}\) and a double-delay linear amplifier referred to as the DD2. The characteristics of this apparatus (1.2 \( \mu \)sec clipping line, maximum gain of 50,000, and low-counting-rate gain shift) were described in detail by Fairstein. \(^{24}\)
Fig. 6. Multiplier spectrum at a scattering angle of 20° (lab) from bombardment of C12 with 50-MeV α particles.
Then the more versatile Goldsworthy system replaced this initial equipment for the silicon detectors. The preamplifier consisted of a charge-sensitive nuvistor amplifier equipped with a two-position coarse gain. The main amplifier is called the Mod VI and has been described by Goldsworthy in a previous report.\textsuperscript{25} The Mod VI could be used in RC, single-delay, or double-delay mode. The time constant could also be varied to permit adjustment for optimum conditions depending on the characteristics of the detector. Typically, for a 0.080-inch detector operating in the RC mode, time constants of 1 μsec (rise) and 5 μsec (clipping) gave best signal-to-noise ratios. The Mod VI is also equipped with a threshold and a post-threshold amplifier, thus making possible the expansion of the useful region of the spectrum.

5. Pulse-Height Analyzer

Two pulse-height analyzers (a Penco 100 channel and a RIDL 400 channel) were used to analyze and count the amplified pulses from the detectors. Each of these analyzers has a coincidence circuit such that signal pulses can be required to possess a corresponding trigger pulse in order to be counted. The presence of upper and lower discriminators on the trigger line allows one to choose a specific group of particles to be analyzed by using the multiplier output as a trigger and discriminating against energy pulses that do not correspond to the selected \( \text{M}^2 \) particles.

6. Over-All Circuitry

The electronic circuitry at the Hilac was greatly simplified and needs no particular attention at this point. Pulses corresponding to particles traversing the first counter were used to trigger the analyzer that recorded the energy pulses of the second detector. The circuitry used for the scattering investigation was also obvious.

A block diagram of the counting equipment for an \((\alpha, \text{d})\) reaction, as set up with a particle identifier, was shown in another report.\textsuperscript{10}
The pulse adder was then introduced to minimize the loss of resolution in the transmission detector. The only difference was that lines from both detectors were sent to a passive adding device whose output became the signal to the analyzer. Such a system was described by Pehl and is not reproduced here. However a later modification of this diagram is worth mentioning with more details.

It has been said before that pulses corresponding to the product $E_0$ and $\Delta E$ are eliminated from the multiplier output by a coincidence requirement. However, for the $(\alpha, d)$ reaction the transmission counter was thick enough to stop all the $\alpha$ particles. Thus a great number of $\Delta E$ pulses was allowed to multiply with the constant $E_0$ and cause a useless jamming of the apparatus.

The system shown in Fig. 7 was then devised to prevent the $\Delta E$ pulses from reaching the particle identifier unless they were in coincidence with an $E$ pulse. This was achieved by adding a linear gate in the line going from the transmission detector to the multiplier. The linear gate was triggered by the pulses from the $E$ line so only the $\Delta E$ pulses that arrive in coincidence with an $E$ pulse were allowed to go through.

Under ideal conditions an identical device should be incorporated in the $\Delta E$ line to the pulse adder so as to prevent the analyzer from being occupied an important amount of time by pulses that will not receive a corresponding trigger.

C. Target Preparation

1. Solid Targets

The $^{12}$C targets were prepared by diluting a solution of colloidal graphite in alcohol and acetone with the same solvents. This solution was then dried on a mirror and the film was allowed to float off in water. The film was then collected on cellophane and the water allowed to evaporate. Self-supporting films about 0.2 mg/cm$^2$ thick
Fig. 7. Complete electronics block diagram.
were obtained with this method. The oxygen impurity was removed by heating the targets to 1400°C in a vacuum and allowing them to cool to below 200°C before exposure to air.

Since the thickness of these thin films was very difficult to measure, thicker carbon targets, prepared by carbonizing circles of Whatman filter paper, were used to normalize each run to an absolute scale. The same heat treatment was used to eliminate the oxygen impurity. The thickness of these filter-paper targets was 2.6 mg/cm^2.

The Mg^{24} target was prepared by evaporation of natural magnesium metal onto a glass plate in vacuum. The film was then peeled off in a mixture of water and alcohol, and the self-supporting target mounted directly on its permanent holder. Unfortunately, attempts using the separated Mg^{24} isotope failed because of the high oxide content of the material. The target used was a 2.57 mg/cm^2 natural magnesium target, i.e. 78% in Mg^{24}.

The Ca^{40} target was prepared by rolling a piece of natural calcium (97% Ca^{40}) down to the appropriate thickness, with great precautions to avoid contact with oxygen. The first step consisted in flattening the metal chip to a foil about 1/32 inch thick. This was done simply by hammering the calcium on a metal plate in the atmosphere. The foil was then introduced into a dry box whose atmosphere was kept inert by a constant nitrogen flow in the presence of P_2O_5 as a drying agent. The oxide layer was then peeled off the surface of the sample with a file and razor blade treatment. This phase of the operation was very important since it is almost impossible to roll the metal if it has an oxide cover. The shiny oxide-free calcium foil was then rolled between hardened steel rollers to its final thickness and mounted directly on the target holder inside the dry box. Targets as thin as 0.7 mg/cm^2 were obtained with this method.
2. Gas Targets

In the 36-inch scattering chamber, gases were bombarded in a gas holder, 3 in. in diameter and 2.5 in. high, mounted in place of the solid-target holder. The gas target had two approximately 120 deg., 0.001 in. thick, and 3/4 inch high Dural windows and could be rotated to permit measurements at any laboratory angle. The system was connected to a manometer and a pumping unit outside the chamber.

With the 10-inch scattering chamber, gases were bombarded by plugging the beam pipe with a 0.001-in. thick Dural window and filling the whole scattering chamber with gas. Again a manometer and a pumping unit allowed one to read and control the target thickness.

For both chambers an additional slit was placed about 8 to 11 inches ahead of the counter collimator to define the solid angle subtended by the detector.

The naturally occurring isotopic mixture was used for $^{12}$C, $^{14}$N, $^{16}$O, $^{32}$S (as H$_2$S), and Ar. The 97% $^{15}$N target was obtained from the Isomet Corporation, and the 98.1% Ne was obtained from the Mound Research Corporation.

D. Data Collection and Reduction Techniques

1. Adjustment of the Electronics

Throughout the circuitry the pulses were adjusted according to the requirements of the different components. During collection of scattering data, for which the use of one detector only reduced the circuitry to one amplifier and a pulse-height analyzer, the only adjustment consisted of keeping the pulses in the operating range of the pulse-height analyzer. The pulses were spread over a given energy region by proper adjustment of the threshold position and the post-amplifier gain.

Again the circuitry used at the Hilac (without the pulse adder and the multiplier) required only similar adjustments and will not be discussed here.
The pulse adder, in order to fulfill its purpose, needed to be fed with pulses from carefully calibrated amplifiers. Deuterons of known energy were scattered from a gold foil into the detectors, and the size of the $\Delta E$ and $E$ signals were adjusted to give pulse heights in the same ratio as the calculated energy deposited in the respective detectors. Small changes in the $\Delta E$ amplifier gain were then made to optimize the resolution of the adder output. Another sensitive check consisted in varying the deuteron energy through different thicknesses of Al absorbers and verifying that a plot of the deuteron energy versus channel number was linear. Once the input pulses were calibrated, the output of the adder was amplified, properly spread in energy, and sent as a signal to the analyzer.

In the trigger line the multiplier was the only piece of equipment requiring particular attention. The initial tuning was done by following the procedure of Briscoe. The adjustment of the constants $E_0$ and $K$ to optimize the deuteron peak separation from the protons and tritons has been described before. Once a good separation between the proton, deuteron, and triton peaks was obtained, the multiplier output was amplified and sent as a trigger to the pulse-height analyzer. A further criterion of satisfactory multiplier operation was to show that the output spectrum was insensitive to the energy of the particles.

The delay lines that appear in the overall circuitry were empirically adjusted to allow the trigger and the signal pulses to fall within the timing requirements of the pulse-height analyzer.

2. Energy Spectra

The energy spectrum is obtained by counting with the analyzer all the $E$ or $(E + \Delta E)$ signals corresponding to a given reaction at one angle.

When the multiplier was used one needed to adjust the upper and lower discriminators properly so as to allow only one type of particle to be counted, in this case the deuteron. This was done by
using the multiplier both as signal and trigger to the analyzer and then setting the lower discriminator on the gate to correspond to the center of the proton-deuteron valley, and the upper discriminator to correspond to the center of the deuteron-triton valley. Then the multiplier was left as a trigger and the added pulse introduced as the signal to be analyzed. Throughout the measurements, the position of the gates of the deuteron peak was checked several times per day.

3. Data Analysis

The first information to be extracted from the energy spectrum is the determination of the energies of the various final states populated by the reaction. The energy calibration of the pulse-height analyzer was achieved in different ways depending on the reaction investigated.

In the electronically simple case of the scattering experiments, a very accurate calibration was achieved with the help of a pulse generator. Immediately after recording each spectrum, pulses from a pulse generator were fed into the front end of the preamplifier. The pulse heights from the generator were varied in about 20 steps by means of a Dekapot potentiometer, thus establishing the relationship between Dekapot dial reading and channel number of the analyzer. The Dekapot dial reading was calibrated by determining the channel number of the elastic peak over an angular range wide enough to allow the energy of the scattered particle to vary according to the kinematics of the reaction. The energy of the elastic peak was computed by a relativistic program and the energy loss in the target was taken into account. This relationship was then used to identify another peak in the spectra whose computed energies were then incorporated in the energy scale.

The use of a pulse generator was not easily adaptable to the more complicated (α, d) circuitry. The calibration of the analyzer was obtained from the scattering of accelerated deuterons by a gold target. The deuteron energy was again calculated from the kinematics
program and by use of various amounts of absorber, or different scattering angles, the energy range up to almost the energy of acceleration of the deuteron could be covered. However, in most cases there was still a gap between this region and the most energetic deuteron from the reaction. This gap was filled gradually through an internal calibration from the energy levels themselves.

First the higher excitation levels falling in the calibrated region were analyzed. Then the levels which at large angle fall in this region were determined and their calculated energy used to compute the corresponding deuteron energy for the same state at smaller angle, thus extending the region of calibration. The same procedure was repeated until the levels from all the energy spectra could be analyzed.

In cases for which the levels of the recoil nucleus were already well known, as in C\textsuperscript{12}(He\textsuperscript{3}, p)N\textsuperscript{14} and O\textsuperscript{16}(He\textsuperscript{3}, p)F\textsuperscript{18}, a strictly internal energy scale was based on the proton energy, as predicted by the kinematics of the reaction for the different levels of excitation.

In other circumstances, when a reaction was observed for the first time, as for Ca\textsuperscript{40}(α, d)Sc\textsuperscript{42} or Ar\textsuperscript{40}(α, d)K\textsuperscript{42}, the energy scale was calibrated by comparison with the known reaction C\textsuperscript{12}(α, d)N\textsuperscript{14}. The amount of energy loss in the targets was taken into account as their thicknesses were very different.

All the levels identified in this work were determined to be of constant value of excitation over a range of angle wide enough to indicate that the reaction was following the kinematics of the particular A(a, b)B transition and not one from an unknown impurity. The values of the quantity were then averaged to establish the excitation of the populated state.

In addition to the identification of a level, its cross section is also a valuable piece of information to be extracted from the energy spectra. The number of counts underneath a peak was totaled and recorded in terms of counts per μC of incident beam. The conversion of
the number of counts per μC into a differential cross section was done by standard methods. This operation needs no particular description in the case of the solid targets.

However, for the gas-target system, the target thickness is determined by the solid angle (Ω) subtended by the defining collimators and thus varies with the angle of observation. The differential cross section was calculated for each angle from the equation

$$\frac{d\sigma}{d\Omega} = \frac{(T + 273) \times \sin \theta \times (l_1 + l_2)^2 \times N \times Z \times 1.66 \times 10^{-6}}{P \times W_1 \times W_2 \times h_2 \times [1 + l_1/l_1]}$$

where \(T\) is the gas-target temperature in degrees centigrade; \(l_1\) and \(l_2\) are the distances from the front collimator to the gas-target center and from the front collimator to the rear collimator, respectively; \(N\) is the number of events recorded for the passage of B μC of incident particles of charge number \(Z\); \(P\) is the gas pressure in cm of mercury; \(n\) is the number of target atoms in each molecule of gas; \(W_1\) and \(W_2\) are the widths of the front and rear slits; \(h_2\) is the height of the rear slit; and \(\theta\) is the scattering angle. All linear dimensions are measured in centimeters. This equation is applicable only if the height of the front slit is large enough to encompass the total height of the incident beam at the target position. In some instances the back collimator was round instead of rectangular; the area of this collimator was then substituted for \(W_2 h_2\) in the equation.

The total cross sections were obtained by integration of the differential cross sections according to the equation

$$\sigma = 2\pi \int_0^\pi \frac{d\sigma}{d\Omega} \sin \theta \ d\theta = 2\pi \int_{-1}^1 \frac{d\sigma}{d\Omega} \ d(\cos \theta)$$

In practice the second expression was evaluated graphically and the range of integration was never from 0° to 180°.
III. EXPERIMENTAL RESULTS

This study was concerned primarily with the capture of two nucleons by the \((\alpha, d)\) stripping reaction. The corresponding \((\text{He}^3, p)\) reactions were also observed on two target nuclei. The scattering of \(\alpha\) particles was investigated in a few cases to obtain additional information about the energy levels observed in the stripping reactions. The results obtained from each reaction are discussed here and further correlation of the experimental measurements appear in Sec. IV.

A. The \((\alpha, d)\) Reactions

1. \(^{12}_C(\alpha, d)^{14}_N, ^{14}_N(\alpha, d)^{16}_O, ^{15}_N(\alpha, d)^{17}_O\)

These three reactions are treated together since they are part of an investigation carried out by Cerny\(^9\) and only new contributions to this data will be discussed here. This earlier work was performed with the 48-MeV \(\alpha\)-particle external beam of the Crocker Radiation Laboratory using a detection system capable of about 500 keV in energy resolution under the best possible conditions.

The \(^{12}_C(\alpha, d)^{14}_N\) reaction was observed more recently with the 50-MeV \(\alpha\)-particle beam of the 88-inch cyclotron. The reaction was investigated over the angular range from 20° to 30° (lab). Deuterons corresponding to 10.2 MeV of excitation in \(^{14}_N\) were included in the range of observation. The detectors consisted of two lithium-drifted silicon crystals; the transmission counter was 0.050 inch thick and the stopping counter 0.090 inch. Figure 8 shows the \(^{14}_N\) energy spectrum obtained at 25° (lab). The 225-keV energy resolution makes possible the identification of some levels unresolved in the previous \((\alpha, d)\) investigation. Table I presents these latest results compared to the levels already known for \(^{14}_N\) (Ref. 27).

A close examination of Fig. 8 and Table I indicates that the 2.31-MeV level, forbidden by angular momentum and parity-selection
Fig. 8. Deuteron energy spectrum from the $^{12}\text{C}(\alpha, d)^{14}\text{N}$ reaction observed at 25° (lab) with 50 MeV alpha particles.
Table I. Comparison of the $^\text{N}^{14}$ levels we observed from the $^\text{C}^{12}(\alpha, \text{d})^\text{N}^{14}$ reaction with those previously reported in this region.

<table>
<thead>
<tr>
<th>Levels identified$^a$</th>
<th>Intensity$^b$</th>
<th>Known energy levels</th>
<th>Shell-model configuration$^c$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>MeV</td>
<td>J</td>
</tr>
<tr>
<td>0</td>
<td>Fairly strong</td>
<td>0</td>
<td>1</td>
</tr>
<tr>
<td>2.31</td>
<td>Weak</td>
<td>3.945</td>
<td>1</td>
</tr>
<tr>
<td>4.91$^e$</td>
<td>Weak</td>
<td>4.91 (0)</td>
<td>-</td>
</tr>
<tr>
<td>5.10$^e$</td>
<td>Strong</td>
<td>5.10</td>
<td>2</td>
</tr>
<tr>
<td>5.69$^e$</td>
<td>Fairly strong</td>
<td>5.69</td>
<td>1</td>
</tr>
<tr>
<td>6.21$^e$</td>
<td>Very weak</td>
<td>6.21 (+)</td>
<td>0</td>
</tr>
<tr>
<td>6.44$^e$</td>
<td>Strong (6.70)</td>
<td>6.44 (6.70)</td>
<td>3</td>
</tr>
<tr>
<td>7.03</td>
<td>Weak</td>
<td>7.03 (7.40)</td>
<td>2</td>
</tr>
<tr>
<td>7.97</td>
<td>Weak</td>
<td>7.97 (7.60)</td>
<td>2</td>
</tr>
<tr>
<td>8.47$^e$</td>
<td>Strong</td>
<td>8.47 (0)</td>
<td>0</td>
</tr>
<tr>
<td>8.7</td>
<td></td>
<td>8.7</td>
<td>0</td>
</tr>
<tr>
<td>8.91</td>
<td></td>
<td>8.91</td>
<td>3</td>
</tr>
<tr>
<td>8.99</td>
<td></td>
<td>8.99</td>
<td>1</td>
</tr>
<tr>
<td>9.00$^f$</td>
<td>Very strong</td>
<td>9.00</td>
<td>5</td>
</tr>
<tr>
<td>9.17</td>
<td></td>
<td>9.17</td>
<td>2</td>
</tr>
<tr>
<td>9.41</td>
<td>Fairly strong</td>
<td>9.41</td>
<td>2</td>
</tr>
<tr>
<td>9.71</td>
<td>Weak</td>
<td>9.71</td>
<td>1</td>
</tr>
<tr>
<td>10.09</td>
<td>Fairly strong</td>
<td>10.09</td>
<td>(1)</td>
</tr>
</tbody>
</table>

$^a$Levels identified through a strictly internal energy scale, thus making these numbers identical to the already known values from Refs. 27 and 28.
Table I. Continued

| \textsuperscript{b} At the angle of observation (25° in the lab). |
| \textsuperscript{c} See Ref. 29. |
| \textsuperscript{d} Assigned a \( (p_{3/2})^{-1} (p_{1/2})^{-1} \) configuration by Ref. 30. |
| \textsuperscript{e} Members of the doublet not completely resolved, although their relative population can be determined. |
| \textsuperscript{f} Spin and parity assigned from Ref. 28 and Sec. IV. |
rules and by isospin conservation, is not made above background at the angle of observation ($25^\circ$ lab). On the other hand the presence of the 8.47, the 9.41, and probably the 9.71-MeV levels suggests an isospin quantum number $T = 0$ for those levels. This spin assignment is in complete agreement with an earlier ($\alpha$, $\alpha$) work leading to the same states of $^{14}$N (Ref. 11).

Since the ($\alpha$, d) reaction consists of the capture of a proton and a neutron by the target nucleus, the most probable levels to be formed in the recoil nucleus will be the ones for which the target configuration is found as the core surrounded by the captured particles in the other available shells. Kurath's intermediate-coupling calculations$^{31}$ in the lp shell indicate the configuration of the $^{12}$C g.s. to be $48\% (p_{3/2})^8 + 40.2\% (p_{3/2})^6 (p_{1/2})^2 + 7.2\% (p_{3/2})^5 (p_{1/2})^3 + 3.4\% (p_{3/2})^4 (p_{1/2})^4$. Thus the levels identified in the $^{12}$C($\alpha$, d)$^{14}$N reaction could be interpreted in terms of this $^{12}$C configuration to which two particles are added.

The position of the $^{14}$N nucleus near the end of the $p$ shell, in addition to the fact that it still contains relatively few nucleons, has made possible many detailed shell-model calculations concerning its configuration. The last column of Table I reproduces the shell-model assignment of the levels according to a recent calculation by True.$^{29}$ It is in very close agreement with the extensive work of Warburton and Pinkston$^{30}$ and with the study of Talmi and Unna.$^{32}$

These shell-model configurations, together with the angular momentum of the levels, can be used to obtain the different L-S components of these levels by expansion of the $J$-$J$ wave function.$^{33}$ The results of this expansion for the levels formed by the ($\alpha$, d) reaction are shown in Table II; the allowed triplet components are enclosed in boxes. The singlet components could contribute only by a spin flip of one of the nucleons of the captured triplet deuteron and are not considered here.
Table II. L-S components for the N\textsuperscript{14} wave functions.

<table>
<thead>
<tr>
<th>Level</th>
<th>j π Configuration</th>
<th>L-S components</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>1 + (p\textsubscript{1/2})\textsuperscript{2}</td>
<td>( \frac{20}{27} \ 3\ D - \frac{1}{27} \ 3\ S + \sqrt{\frac{6}{27}} \ 1\ P )</td>
</tr>
<tr>
<td>3.95</td>
<td>1 + (p\textsubscript{3/2}) (1/2)</td>
<td>( \frac{5}{24} \ 3\ D - \frac{16}{54} \ 3\ S + \sqrt{\frac{6}{54}} \ 1\ P + \sqrt{\frac{27}{54}} \ 3\ P )</td>
</tr>
<tr>
<td>4.91</td>
<td>0 - (p\textsubscript{1/2}) (s\textsubscript{1/2})</td>
<td>( 1 \ 3\ P )</td>
</tr>
<tr>
<td>5.10</td>
<td>2 - (p\textsubscript{1/2}) (d\textsubscript{5/2})</td>
<td>( -\sqrt{\frac{7}{225}} \ 3\ F - \sqrt{\frac{108}{225}} \ 3\ P + \sqrt{\frac{30}{225}} \ 3\ D + \sqrt{\frac{30}{225}} \ 1\ D )</td>
</tr>
<tr>
<td>5.69</td>
<td>1 - (p\textsubscript{1/2}) (s\textsubscript{1/2})</td>
<td>( \sqrt{\frac{2}{3}} \ 3\ P + \sqrt{\frac{1}{3}} \ 1\ P )</td>
</tr>
<tr>
<td>5.83</td>
<td>3 - (p\textsubscript{1/2}) (d\textsubscript{5/2})</td>
<td>( \sqrt{\frac{4}{9}} \ 3\ F - \sqrt{\frac{2}{9}} \ 3\ D + \sqrt{\frac{2}{9}} \ 1\ F )</td>
</tr>
<tr>
<td>6.21</td>
<td>1 + (s\textsubscript{1/2})\textsuperscript{2}</td>
<td>( 1 \ 3\ S )</td>
</tr>
<tr>
<td>6.44</td>
<td>3 + (s\textsubscript{1/2}) (d\textsubscript{5/2})</td>
<td>( \frac{1}{3} \ 3\ D )</td>
</tr>
<tr>
<td>7.03</td>
<td>2 + (p\textsubscript{3/2}) (p\textsubscript{1/2})</td>
<td>( \sqrt{\frac{2}{6}} \ 3\ D + \sqrt{\frac{1}{6}} \ 3\ P - \sqrt{\frac{5}{6}} \ 1\ D )</td>
</tr>
<tr>
<td>7.97</td>
<td>2 - (p\textsubscript{1/2}) (d\textsubscript{3/2})</td>
<td>( \frac{112}{150} \ 3\ F + \frac{2}{150} \ 3\ P - \frac{5}{150} \ 3\ D + \frac{30}{150} \ 1\ D )</td>
</tr>
<tr>
<td>9.00</td>
<td>5 + (d\textsubscript{5/2})\textsuperscript{2}</td>
<td>( 1 \ 3\ G )</td>
</tr>
<tr>
<td>9.71</td>
<td>1 + (d\textsubscript{5/2})\textsuperscript{2}</td>
<td>( -\sqrt{\frac{4}{25}} \ 3\ D + \sqrt{\frac{7}{25}} \ 3\ S + \sqrt{\frac{14}{25}} \ 1\ P )</td>
</tr>
</tbody>
</table>
A relationship can be established between the allowed triplet components and the selective population of the levels. Figure 9 shows the intensity at $25^\circ$ of the levels divided by the factor $(2J + 1)$ (see Sec. IV. A. 2 and Ref. 34). The dotted lines correspond to the intensity of the levels that are made through single L-S components: the 9.0, 6.44, 4.91, and 6.21-MeV levels corresponding to the $^3G$, $^3D$, $^3P$, and $^3S$ components, respectively. The intensity of a pure $^3F$ transition is calculated from the $\sqrt{\frac{14}{9}}^3F$ component of the 5.83-MeV level.

Figure 9 shows clearly that the cross section decreases with L in the following order:

$$^3G > ^3F > ^3D > ^3P > ^3S$$

This situation is in complete agreement with the grazing-collision nature of the stripping reaction, as discussed in Sec. IV. A. 1.

The levels of partial or mixed allowed components are also included in Fig. 9. The populations of the ground state, the 3.95, 5.10, and 5.69-MeV levels are in good agreement with their expected intensities from the components through which they can be made. The 7.03-MeV level is made much smaller than expected. The 7.97-MeV level is also populated less than expected from its $\sqrt{\frac{112}{150}}^3F$ component. However, the unassigned 8.47-MeV level, observed also via ($\alpha$, $\alpha'$) reaction, would be a good candidate for the configuration proposed for the 7.97-MeV state. In the assumption of a misassignment, the population of the 8.47-MeV level is plotted on Fig. 9 as being a 2 - $(p_{1/2} d_{5/2})$ level; the agreement between its population and the expected intensity from a $\sqrt{\frac{112}{150}}^3F$ component is remarkable. Such a misassignment has been suggested previously. This discussion must unfortunately remain qualitative since a complete angular distribution would be necessary to reach any conclusion.

The spin assignment and the mechanism of formation of the giant peak at 9.00-MeV is treated in detail in Sec. IV. It is shown
Fig. 9. Statistically weighted population of the levels of \( \text{N}^{14} \) formed by the \( \text{C}^{12}(\alpha, d)\text{N}^{14} \) reaction at 25° (lab). The dotted lines indicate the intensity of the levels formed by pure \( ^3S \), \( ^3P \), \( ^3D \), \( ^3F \), and \( ^3G \) components.
that this level is formed by two nucleons, captured in the $d_{5/2}$ shell, which couple their 5 units of angular momentum with the $0^+$ core to give a $J = 5$ state. The proposed configuration is confirmed by the absence of the 9.0-MeV level in the $\alpha$-particle energy spectra from the $^{16}(d, \alpha)^{14}$ reaction. This statement is valid only for the assumption of a pickup mechanism for the $(d, \alpha)$ reaction, since a knockout process could promote the captured deuteron to the $d_{5/2}$ shell if enough momentum were available. Further confirmation of the proposed $(d_{5/2})^2$ configuration of the 9.0-MeV level was obtained by a study of the $N^{14}(\alpha, \alpha')N^{14}$ reaction (see Sec. III. C). Inelastic scattering should populate strongly those levels in $N^{14}$ that can be made by promotion of a single nucleon from its ground-state configuration. The $(d_{5/2})^2$ level is thus expected to be absent and indeed it was not identified in the $(\alpha, \alpha')$ investigation. Figure 10 presents the angular distribution of this level extracted from the earlier $C^{12}(d, \alpha)^{14}$ data. The 8.47- and 9.41-MeV levels could not be resolved in the previous work and are thus included in the angular distribution of the 9.00-MeV level. The value of 7.0 mb obtained for the cross section of the 9.0-MeV level integrated over the angular range from 20.4 to 78.2 deg (c.m.) is thus slightly inaccurate. A limit of 17%, based on the relative population of these three levels at 25° (lab), is set to the accuracy of the cross section of the 9.0-MeV level.

The core of the $C^{12}$ nucleus has 0 units of angular momentum and thus only one giant peak was observed in the $C^{12}(\alpha, d)^{14}$ reaction. However the ground state of $N^{14}$ has 1 unit of angular momentum and the capture of a deuteron in the $d_{5/2}$ shell will allow the formation of three levels of the configuration $[(d_{5/2})^2 + 1]J_f$, where $J_f$, the spin of the final states, is 6, 5 or 4 units of angular momentum. The $N^{14}(\alpha, d)^{16}$ reaction was previously investigated at the 60-inch cyclotron. The range of excitation energy included in the deuteron spectrum was not quite large enough to allow the three
Fig. 10. Angular distribution of deuterons from formation of the 9.0-MeV level of N^{14} by the C^{12}(α, d)N^{14} reaction.
members of the expected triplet to be observed. Figure 11 shows the energy spectrum of the reaction at 15° lab. The 14.7-MeV, the 16.2 MeV, and maybe the 17.2-MeV levels are identified as the \((d_{5/2})^2\) states. The angular distribution of the 14.7-MeV and 16.2-MeV levels is presented in Fig. 12.

The same argument that predicted three strongly excited \((d_{5/2})^2\) levels in the \(N^{14}(\alpha, d)^{16}\) investigation will justify two peaks for the \(N^{15}(\alpha, d)^{17}\) reaction since the \(N^{15}\) core has 1/2 unit of angular momentum. Figure 13 shows the energy spectrum of this reaction observed at the 60-inch cyclotron; the deuteron-energy spectrum is dominated by two highly populated levels at 7.6 and 9.0-MeV excitation. Figure 14 shows the angular distributions of these two levels computed from the previous data.

2. \(O^{16}(\alpha, d)^{F^{18}}\)

The \(O^{16}(\alpha, d)^{F^{18}}\) reaction was investigated with the 48-MeV \(\alpha\)-particle beam of the 60-inch cyclotron. Figure 15 shows a typical multiplier spectrum of \(O^{16}\) bombarded by 48-MeV \(\alpha\) particles. Figure 16 shows an energy spectrum of the reaction observed at 15° lab. This particular spectrum was obtained with two Li-drifted silicon detectors: a transmission counter 0.030-in. thick and a stopping detector 0.145 in. thick. The pulse adder was incorporated in the circuitry and the energy resolution of the system was about 350 keV. The angular range from 11 to 72 deg (lab) was investigated.

The \(O^{16}(\alpha, d)^{F^{18}}\) reaction was first observed by Aguilar\(^{36}\) and his co-workers during a study of the scattering of 38-MeV \(\alpha\) particles from \(O^{16}\). They reported the angular distribution of one level of \(F^{18}\) that was attributed to the ground state. However, this attribution was found to be a mistake and the level actually observed was the 1.1-MeV level of \(F^{18}\)\(^{37}\).

The angular distribution of the ground state of \(F^{18}\) is shown in Fig. 17. The shells available for the captured particles are the
Fig. 11. Deuteron-energy spectrum from the $^1H(\alpha, d)^{16}$ reaction observed at $15^\circ$ (lab) with 47-MeV $\alpha$ particles.
Fig. 12. Angular distribution of deuterons from the $^7\text{Li}(\alpha, d)^{16}\text{O}$ reaction to the 14.7-MeV (O) and 16.2-MeV (●) levels.
Fig. 13. Deuteron-energy spectrum from the $^N_{15}(\alpha,d)^{17}$ reaction observed at $15^\circ$ (lab) with 47-MeV $\alpha$ particles.
Fig. 14. Angular distributions of deuterons from the $^{15}\text{N}(\alpha, d)^{17}\text{O}$ reaction to the 7.6-MeV (O) and 9.0 MeV (●) levels.
Fig. 15. Multiplier spectrum at a scattering angle of $15^\circ$ (lab) from bombardment of $O^{16}$ with 50-MeV $\alpha$ particles.
Fig. 16. Deuteron energy spectrum from the $^{16}(\alpha, d)^{18}$ reaction observed at $15^\circ$ (lab) with 47-MeV $\alpha$ particles.
Fig. 17. Angular distribution of deuterons from formation of the ground state of $^18\text{F}$ by the $^{16}\text{O}(\alpha, d)^{18}\text{F}$ reaction.
The single-nucleon levels of \(^{17}\)O and \(^{17}\)F illustrate the proximity of the \(s_{1/2}\) and the \(d_{5/2}\) in this region. A theoretical calculation by Elliott and Flowers predicted the ground-state wave function for the \(^{18}\)F nucleus to be a highly mixed function. The various components of the wave function are

\[
\psi = 0.58 (d_{5/2})^2 + 0.57 (d_{5/2} s_{1/2}) - 0.19 (d_{3/2})^2
- 0.02 (d_{5/2} s_{1/2}) + 0.55 (s_{1/2})^2
\]

Possibly such a high degree of admixture would account for the slowly varying pattern of the angular distribution.

Figure 18 shows the angular distribution of the 1.1-MeV level of \(^{18}\)F. This strongly populated state is described as the \((d_{5/2})^2 J = 5\) level of \(^{18}\)F, in complete agreement with the spin \(5^+\) assigned previously to this level. The forward-peaking angular distribution resembles the one reported by Aguilar but there is less scattering of the data points. A value of 11.2 mb was obtained for the cross section of the 1.1-MeV level integrated over the angular range from \(15^\circ\) to \(72.7^\circ\) (c.m.).

More recently the \(^{16}\)O(\(\alpha\), d)\(^{18}\)F reaction has been observed at a few angles with the 40-MeV \(\alpha\)-particle beam of the 88-inch cyclotron. These results are used to investigate if the population of the gross-structure peak is influenced by a different bombarding energy. Classically it is required that enough linear momentum must be available to satisfy the relation \(Q R > L\), where \(L\) is the number of units of angular momentum transferred in the reaction, \(R\) is the interaction radius defined by

\[
R = 1.3 (16^{1/3}) + 1.5
\]

and \(Q\) is the vector difference of the linear momentum vectors (Sec. IV. B). The kinematics of the reaction reveals that at 48 MeV and 40 MeV \(Q R\) is similar and satisfies the classical requirement. Table III
Fig. 18. Angular distribution of deuterons from formation of the ground state of $^3\text{He}$ by the $^{16}\text{O}(\alpha, \text{d})^3\text{He}$ reaction (1.1-MeV level).
Table III. Relative population of the 1.1 MeV level of $^{18}$F by the $(\alpha, d)$ reaction observed at 40 and 48 MeV.

<table>
<thead>
<tr>
<th>c.m. angle</th>
<th>E</th>
<th>QR</th>
<th>Relative population$^a$</th>
</tr>
</thead>
<tbody>
<tr>
<td>24.9</td>
<td>40</td>
<td>6.5</td>
<td>25.1</td>
</tr>
<tr>
<td></td>
<td>48</td>
<td>7.3</td>
<td>40.6</td>
</tr>
<tr>
<td>36.9</td>
<td>40</td>
<td>7.4</td>
<td>23.0$^b$</td>
</tr>
<tr>
<td></td>
<td>48</td>
<td>7.8</td>
<td>12.4</td>
</tr>
<tr>
<td>18.6</td>
<td>40</td>
<td>6.2</td>
<td>39.8</td>
</tr>
<tr>
<td></td>
<td>48</td>
<td>6.4</td>
<td>42.0</td>
</tr>
<tr>
<td>48.9</td>
<td>40</td>
<td>8.3</td>
<td>8.5</td>
</tr>
<tr>
<td></td>
<td>48</td>
<td>8.9</td>
<td>9.1</td>
</tr>
</tbody>
</table>

$^a$ Ratio of the population of the 1.1-MeV level to the ground state of $^{18}$F.

$^b$ The small number of ground-state counts recorded at this angle make the relative value highly uncertain.
shows a comparison of the population of the 1.1-MeV level relative to
the ground state when the bombarding energy was varied. As expected
from the kinematics, no systematic trend in the relative population
of the \( (d_{5/2})^2 J = 5 \) level was found.

3. \( \text{Ne}^{20}(\alpha, d)\text{Na}^{22} \)

The \( \text{Ne}^{20}(\alpha, d)\text{Na}^{22} \) reaction was observed with the 45-MeV \( \alpha \)
beam of the 88-inch cyclotron. The neon gas pressure was 37.5 cm Hg
and the beam energy was degraded by 1 MeV between the entrance window
and the center of the gas target. The pulses from a 0.050-inch lithium-drifted transmission counter were added to the pulses coming from
the 0.090-inch lithium-drifted stopping detector. The linear gate
described in Sec. I. B. 5 was used in the \( \Delta E \) line to allow the multi­
plier to "see" only those \( \Delta E \) pulses that had corresponding \( E \) pulses
in coincidence. The energy resolution of the system was 300 keV.

Figure 19 shows the multiplier spectrum measured at 25° lab. The
reaction was observed over the angular range from 10° to 60° (lab).

Figure 20 shows the deuteron-energy spectrum at 15° lab.
Since there were no previous \( \text{Ne}^{20}(\alpha, d)\text{Na}^{22} \) data available, the energy
scale was calibrated from the \( \text{C}^{12}(\alpha, d)\text{N}^{14} \) reaction. The difference
in energy lost by the outgoing deuteron in the two targets was taken
into account. Table IV reproduces a list of the levels identified
compared with the already known levels of \( \text{Na}^{22} \).

The ground state of \( \text{Na}^{22} \) is formed in small amounts by the
(\( \alpha, d \)) reaction. The level reported at 0.79 MeV appears to be a
doublet formed by a level at 0.6 and 0.9 MeV. The very small popula­
tion of these excited states makes final identification difficult.
The same problem arises for the identification of the 3.74-, 5.29-, and
5.95-MeV levels.

The highly populated state at 1.53 MeV is described in Sec.
IV as being a \( (d_{5/2})^2 \) level. The strongly forward-peaking angular
distribution of this level is shown in Fig. 21. Temmer and
Fig. 19. Multiplier spectrum at a scattering angle of $25^\circ$ (lab) from bombardment of Ne$^{20}$ with 45-MeV $\alpha$ particles.
Fig. 20. Deuteron-energy spectrum from the Ne$^{20}$ (α, d)Na$^{22}$ reaction observed at 15° with 44-MeV α particles.
Fig. 21. Angular distributions from the Ne\textsuperscript{20}(α, d)Na\textsuperscript{22} reaction to the 1.53-MeV (○) and 7.46-MeV (●) levels.
Table IV. Energy levels identified by the Ne$^{20}(\alpha, d)$Na$^{22}$ reaction.

<table>
<thead>
<tr>
<th>Levels identified</th>
<th>Intensity$^a$</th>
<th>Levels known</th>
<th>J</th>
<th>$\Pi$</th>
<th>T</th>
</tr>
</thead>
<tbody>
<tr>
<td>g.s.</td>
<td>0.15</td>
<td>g.s.</td>
<td>3</td>
<td></td>
<td>+</td>
</tr>
<tr>
<td>$0.79 \pm 0.3$</td>
<td>Very weak</td>
<td>0.587</td>
<td>1</td>
<td></td>
<td>+</td>
</tr>
<tr>
<td></td>
<td></td>
<td>0.660</td>
<td>0</td>
<td>+</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td></td>
<td>0.892</td>
<td>(1)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$1.53 \pm 0.1$</td>
<td>2.06</td>
<td>$1.532^d$</td>
<td>(5)</td>
<td></td>
<td>+</td>
</tr>
<tr>
<td></td>
<td></td>
<td>1.942</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>1.95</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>1.988</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>2.217</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>2.574</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$2.98 \pm 0.1$</td>
<td>0.54</td>
<td>$2.973^d$</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>3.065</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>3.527</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$3.74 \pm 0.2$</td>
<td>Weak</td>
<td>3.71</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>3.949</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>4.07</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>4.32</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>4.36</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>4.47</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>4.53</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$4.68 \pm 0.1$</td>
<td>Fairly strong</td>
<td>4.60</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>4.73</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>4.77</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$5.29 \pm 0.3$</td>
<td>Weak</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$5.95 \pm 0.2$</td>
<td>Weak</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$6.62 \pm 0.2$</td>
<td>0.51</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Table IV. Continued

<p>| | | | | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>7.46 ± 0.2</td>
<td>1.07</td>
<td>7.474</td>
<td>(7 +) \textsuperscript{d}</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>7.57</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>7.71</td>
<td></td>
<td></td>
</tr>
<tr>
<td>7.85 ± 0.2</td>
<td>Strong</td>
<td>7.81</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>7.90</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>7.98</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>8.04</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

\textsuperscript{a}The numbers are the cross section in mb integrated over the angular range from 10° to 52.5° lab.

\textsuperscript{b}See Ref. 43.

\textsuperscript{c}Unresolved doublet.

\textsuperscript{d}Assigned by this work.
Heydenburg previously observed the $^{20}\text{Ne}^2(\text{He}^3, p)^{22}\text{Na}$ reaction, which should also populate the $(d_{5/2})^2$ level very strongly. However their investigation was carried out at a bombarding energy of 3.5 MeV, thus making impossible any relative population comparison. It is also noteworthy that the formation of the 1.53-MeV level by the $^{24}\text{Mg}^2(d, \alpha)^{22}\text{Na}$ reaction does not alter the $(d_{5/2})^2$ assignment, since the $d_{5/2}$ shell is already populated in this target nucleus.

The other strongly populated level, at 7.46 MeV, is described in Sec. IV as probably being a $(f_{7/2})^2$ level. A level was previously reported at 7.47 MeV through a $(p, \gamma)$ investigation. No spin assignment was suggested for this 7.47-MeV state, but since the $(p, \gamma)$ reaction would favor a single-nucleon level it is probably a different state from the one identified here. Otherwise the presence of a strong $f_{7/2}$ component would be necessary in the $^{21}\text{Ne}$ wave function. The angular distribution of the 7.46-MeV state appears in Fig. 21 together with the one of the 1.53-MeV level.

The population of both the $(d_{5/2})^2$ and the $(f_{7/2})^2$ levels is believed to have been seen also in a brief investigation of the $^{24}\text{Mg}^2(\alpha, d)^{26}\text{Al}$ reaction. Figure 22 shows the deuteron energy spectrum of the $^{24}\text{Mg}^2(\alpha, d)^{26}\text{Al}$ reaction obtained at 25° (lab) under the same experimental conditions described for the $^{20}\text{Ne}$ nucleus.

The strongly populated ground state of $^{26}\text{Al}$ is a known 5+ level (Ref. 43) and is assigned here a $(d_{5/2})^2$ configuration. The other strongly populated level, at 6.91 MeV, could be the corresponding $(f_{7/2})^2$ level. The high content of magnesium oxide in the target accounts for the presence of the 1.1-MeV level of $^{18}\text{F}$. The high-level density of $^{26}\text{Al}$ (Ref. 43) makes impossible any attempt to obtain significant angular distributions for any of these levels.

4. Ca$^{40}(\alpha, d)^{42}\text{Sc}$

The Ca$^{40}(\alpha, d)^{42}\text{Sc}$ reaction was first observed during the last days of the 60-inch cyclotron, but a more complete investigation was
Fig. 22. Deuteron energy spectrum from the $^{24}\text{Mg} (\alpha, \text{d})^{26}\text{Al}$ reaction observed at 25° (lab) with 45-MeV $\alpha$ particles.
carried out with the 50-MeV alpha beam of the 88-inch cyclotron. The reaction was observed over the angular range from 12.5 deg to 60 deg (lab). Pulses from the 0.050-inch lithium-drifted transmission detector were added to the pulses from the 0.090-inch stopping counter. The linear gate (see Sec. I. B. 5) was also used in the \(\Delta E\) line. The multiplier spectrum is presented in Fig. 23.

Figure 24 shows the deuteron energy spectrum at 40° lab. The energy resolution of the system was 230 keV on the Ca target. The energy scale was obtained from the \(^{12}\text{C}(\alpha, d)^{14}\text{N}\) reaction. The presence of oxygen in the calcium target provided an additional reference point since the 1.1-MeV level of \(^{18}\text{F}\) was easily identified.

Table V presents a list of the levels formed by the \((\alpha, d)\) reaction compared with the levels seen in a previous \((\text{He}^3, p)\) investigation. This comparison is interesting because of the selection rules involved. In the case of the \(^{40}\text{Ca}(\text{He}^3, p)^{42}\text{Sc}\) reaction, the captured deuteron in the \(f_7/2\) shell can be in a triplet or singlet state, thus allowing the proton and the neutron to couple to any value of angular momentum between 0 and 7. However in the \(^{40}\text{Ca}(\alpha, d)^{42}\text{Sc}\) investigation, a deuteron in its triplet state is captured and the only levels allowed for a "deuteron" in the \(f_7/2\) shell are those containing an allowed triplet component. The \(J-J\) to \(L-S\) coupling expansion of a neutron and a proton in the \(f_7/2\) shell, presented in Table VII, shows that only the odd-spin levels have such a triplet component and are thus allowed in the \((\alpha, d)\) reaction.

The ground state of \(^{42}\text{Sc}\) is not made by the \((\alpha, d)\) reaction, confirming the 0+, \(T = 1\) assignment to this level. Janecke has shown that, like the known case of \(^{34}\text{Cl}\), the lowest \(T = 1\) state of \(^{42}\text{Sc}\) will be lower than the lowest \(T = 0\) level. From a rough graphical estimate he predicts a value of about 0.5 MeV for the energy difference between the lowest \(T = 0\) and \(T = 1\) states for odd-odd nuclei of mass number \(>\) forty. This estimate is consistent with the value of the first excited state identified at 0.60 MeV above the ground state.
Fig. 23. Multiplier spectrum at a scattering angle of 20° (lab) from bombardment of Ca$^{40}$O with 50-MeV α particles.
Fig. 24. Deuteron energy spectrum from the \(^{40}\text{Ca}(\alpha, \text{d})^{42}\text{Sc}\) reaction observed at 40° (lab) with 50-MeV \(\alpha\) particles.
Table V. Energy levels of $^{42}$Sc formed by the ($\alpha$, d) and ($\text{He}^3$, p) reactions.

<table>
<thead>
<tr>
<th>Ca$^{40}$(He$^3$, p)$^{42}$</th>
<th>Ca$^{40}$((\alpha,) d)$^{42}$</th>
<th>J</th>
<th>(\Pi)</th>
<th>T</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td></td>
<td>0</td>
<td>+</td>
<td>1</td>
</tr>
<tr>
<td>0.617</td>
<td>0.60 ± 0.1</td>
<td>7</td>
<td>+</td>
<td>0</td>
</tr>
<tr>
<td>1.035</td>
<td>even</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1.509</td>
<td>1.43 ± 0.1</td>
<td>odd</td>
<td></td>
<td>0</td>
</tr>
<tr>
<td>1.958</td>
<td>even</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2.248</td>
<td>(2.25)</td>
<td>(odd)</td>
<td>(0)</td>
<td></td>
</tr>
<tr>
<td>2.998</td>
<td>3.0 ± 0.1</td>
<td>(odd)</td>
<td>0</td>
<td></td>
</tr>
<tr>
<td></td>
<td>3.55 ± 0.15</td>
<td></td>
<td>0</td>
<td></td>
</tr>
<tr>
<td></td>
<td>4.23 ± 0.15</td>
<td></td>
<td>0</td>
<td></td>
</tr>
<tr>
<td></td>
<td>4.75 ± 0.1</td>
<td></td>
<td>0</td>
<td></td>
</tr>
<tr>
<td></td>
<td>5.28 ± 0.1</td>
<td></td>
<td>0</td>
<td></td>
</tr>
</tbody>
</table>

\(a\) See Ref. 44.

\(b\) This level is probably the 5+ level of the (f$^{7/2}$)$_2$ configuration.
The 0.60-MeV state is highly populated by the \((\alpha, d)\) reaction and is believed to be the \((f_{7/2})_7^2\) level.

The levels at 0, 1.035, and 1.958 MeV identified in the \((\text{He}^3, p)\) investigation were not seen in our \((\alpha, d)\) work, thus indicating that if they belong to the \((f_{7/2})_7^2\) configuration, they have even spin values. On the other hand, the levels observed at 0.60, 1.43, 2.25, and 3.0 MeV have been seen in both cases and are then probably the other odd-spin states. This is in disagreement with the assignments (except for those of the 0.60-MeV and 2.25-MeV levels) used in theoretical calculations by Bayman and Ginnchilo. The 1.43-MeV level is strongly populated and its angular distribution is forward peaking like the other gross structure levels mentioned. A spin of 2 units of angular momentum from the \((f_{7/2})_7^2\) configuration has been assigned to this excited state, but such a transition is forbidden in the \((\alpha, d)\) reaction. The same work has suggested the \((f_{7/2})_5^2\) configuration to be the 1.958-MeV level, but again this is in contradiction with the \((\alpha, d)\) results. It is possible that these two assignments are inverted and that the 1.43-MeV level is of the \((f_{7/2})_5^2\) configuration. Figure 25 shows the angular distribution of the 0.60-MeV and the 1.43-MeV levels. The integrated cross sections over the angular range from 12.5 to 60 deg (lab) give values of 4.34 and 1.52 mb for the 0.60- and 1.43-MeV states, respectively.

A brief investigation of the \(^{40}\text{Ar} (\alpha, d)K^{42}\) reaction was carried out with the 45-MeV \(\alpha\) beam of the 88-inch cyclotron in an attempt to identify the \((f_{7/2})_7^2\) level in \(^{42}\text{K}\). Figure 26 shows the deuteron energy spectrum observed at 20 deg (lab). The spectrum is again dominated by one highly populated level at 1.87-MeV excitation, believed to be the \((f_{7/2})_7^2\) level. Figure 27 shows the angular distribution of the 1.87-MeV state. The cross section of this level, integrated over the angular range from 11.6 to 53.8 deg (c.m.), was 1.6 mb.

Another attempt to identify the level of the \((f_{7/2})_7^2\) configuration was made in the region between mass numbers 42 and 26. The
Fig. 25. Angular distribution from the reaction $^{40}\text{Ca}(\alpha, d)^{42}\text{Sc}$ to the 0.60-MeV (○) and 1.43-MeV (●) levels.
Fig. 26. Deuteron energy spectrum from the $^{40}\text{Ar}(\alpha, d)^{42}\text{K}$ reaction observed at $20^\circ$ (lab) with 44-MeV $\alpha$ particles.
Fig. 27. Angular distribution of deuterons from formation of the 1.87-MeV level of \(^{42}\text{K}\) by the \(^{40}\text{Ar}(\alpha, \text{d})^{42}\text{K}\) reaction.

\(\bigcirc\), 44 MeV \(\alpha\); \(\Box\), 48 MeV \(\alpha\).
$^{32}\text{S}(\alpha, d)^{34}\text{Cl}$ reaction was observed with the 48-MeV $\alpha$ beam of the 60-inch cyclotron. Figure 28 shows the deuteron energy spectrum recorded at 15 deg (lab). Once more the spectrum is dominated by a highly populated level identified as the 5.2-MeV level of $^{34}\text{Cl}$.

**B. The ($\text{He}_3^3$, p) Reactions**

The capture of a proton-neutron pair in the ($\text{He}_3^3$, p) reaction was also investigated for $^{12}\text{C}$ and $^{16}\text{O}$ target nuclei. The two-nucleon promotion nature of the ($\text{He}_3^3$, p) reactions should allow the $(d_5/2)^2$ levels identified in the ($\alpha$, d) investigation to be again preferentially populated.

The $^{12}\text{C}(\text{He}_3^3$, p)$^{14}\text{N}$ reaction was observed with the 31.2-MeV $\text{He}_3^3$ ion beam of the Hilac. The outgoing protons were detected in two separate counter telescopes. One system consisted of two lithium-drifted semiconductor detectors: a 0.050-inch transmission detector and a 0.150-inch stopping counter. The other system was a 0.012-inch CsI(Tl) crystal followed by a 0.5-inch NaI(Tl) crystal. Theoretically the semiconductor counter is capable of better resolution than the NaI(Tl) crystal, but little difference was observed under the experimental conditions due to the large amount of absorber required either to stop the deuterons or to confine the protons to the intrinsic region of the semiconductor detector. Figure 29 shows the proton energy spectrum at 40° (lab). The energy resolution was typically 700 keV. The investigation was carried out over the angular range from 9.5 to 157 deg (lab).

Figure 30 shows the angular distribution of the ground state, 2.31-, and 3.95-MeV levels. The ground state and 3.95-MeV levels have been previously observed at bombarding energies from 1.30 to 6.05 MeV by Bromley, Johnston, and Sweetman. These-low energy results have been studied by Bromley, who concluded from the increasingly forward-peaking shape and the energy dependence of the angular distributions that these transitions showed characteristics of both
Fig. 28. Deuteron energy spectrum from the $^{32}\alpha, d)^{31}\alpha$ reaction observed at 15 (lab) with 47-MeV $\alpha$ particles.
Fig. 29. Proton energy spectrum from the $^{12}\text{C}(\text{He}^3, \text{p})^{14}\text{N}$ reaction observed at $40^\circ$ (lab) with 31.2-MeV $\text{He}^3$ particles.
Fig. 30. Angular distributions from the $^6$C $(\text{He}, p)^7\text{N}$ reaction to the ground state (○), 2.31-MeV (□), and 3.95-MeV (△) levels.
compound-nucleus and direct-interaction mechanisms. The same comparative study showed that the angular distribution of the 2.31-MeV level, observed at bombarding energies from 1.89 to 6.05 MeV, was already forward peaking at the highest bombarding energy.

The $^4\text{He}^3(p)^{14}\text{N}$ reaction observed recently by Priest, using a bombarding energy of 13.9 MeV, is thus expected to take place to a large extent by a direct interaction. An interesting comparison between the angular distributions of the transitions observed at 13.9 and 31.2 MeV can be made. However comparison of the same transition at different energies implies the use of a model, and any conclusion reached will be restricted by the imperfections of this model.

The $(\text{He}^3, p)$ reaction was first theoretically studied by El Nadi and Newns; the expressions for the angular distributions are quite complicated but they can be approximated by,

$$\frac{d\sigma}{d\Omega} \propto \sum_L [A_L(A^L) J_L(QR)]^2$$ (1)

where $L$ is the orbital momentum brought in by the captured nucleons, $A_L$ is a nuclear factor, and $J_L$ is the Bessel function of order $L$ and of argument $QR$ (see Sec. IV. B. 2). The two-nucleon stripping theory formulated by Glendenning for the $(\alpha, \alpha)$ reaction has been modified to adapt it to the $(\text{He}^3, p)$ reaction. This plane-wave theory can also be approximated to Eq. (1), and calculations involving the complete and approximated form for fitting the angular distribution of the g.s., 2.31-, and 3.95-MeV transitions have shown the validity of the approximation.

With the assumption that the reaction proceeds by stripping and the differential cross section is represented by Eq. (1), the angular distribution of the g.s., 2.31-, and 3.95-MeV levels, measured at 13.9 and 31.2 MeV, should be aligned when plotted versus $QR$. Figures 31, 32, and 33 illustrate the agreement between the angular distributions, especially at small angles; however a different radius had to be used at the two bombarding energies. At 13.9 MeV the interaction radius used was 37% larger than the radius used at 31.2 MeV.
Fig. 31. Differential cross sections of the ground state of $^{14}N$ from $^{12}\text{C}(\text{He}^3,p)^{14}N$ observed with bombarding energies of 13.9 MeV (□) and 31.2 MeV (○).
Fig. 32. Differential cross section of the 2.31-MeV level of $^N_{14}$ from $^{12}\text{C}^3(\text{He}^3, p)^{14}_N$ observed with bombarding energies of 13.9 MeV (□) and 31.2 MeV (○).
Fig. 33. Differential cross section of the 3.95 MeV level of $\text{N}^{14}$ from $\text{C}^{12}$(He$^3$, p)$\text{N}^{14}$ observed with bombarding energies of 13.9 MeV (□) and 31.2 MeV (○).
The bigger radius at lower energy follows the trend already noticed\(^5^8\) in the (d, p) stripping reaction.* The physical significance of a larger interaction radius for a lower bombarding energy is difficult to ascertain, since the degree of distortion is neglected in the simple model used for comparison. An investigation of this radius of interaction bombarding-energy dependence would be valuable and easy to perform with the variable-energy beam of the 88-inch cyclotron.

The levels favored by the (He\(^3\), p) transition should be of the same character as those observed previously in the \(^{12}\text{C}(\alpha, d)^{14}\text{N}\) reaction. Table VI presents a list of the levels populated by the (He\(^3\), p) reaction compared with those observed in the \(^{12}\text{C}(\alpha, d)^{14}\text{N}\) investigation (see Sec. II. A. 1). The \((p_\frac{1}{2})^2 O + T = 1\) level at 2.31 MeV, which was forbidden in the (\(\alpha, d\)) transition, is allowed and strongly populated. The core-excited 3.95-MeV level is populated to almost the same extent as the ground state. This is in marked contrast to the (\(\alpha, d\)) results. It is unfortunate that the 7.03-MeV level of similar \((p_\frac{3}{2})^7(p_\frac{1}{2})^3\) configuration could not be resolved in this work.

The doublets at 4.91, 5.10 MeV and at 6.21, 6.44 MeV are strongly populated. The other doublet observed at 5.69, 5.83 MeV in the (\(\alpha, d\)) investigation does not seem to be made by the (He\(^3\), p) reaction, although the poor energy resolution (700 keV) of the system prevents any final conclusion to be made about this pair.

The 9.0-MeV level was populated approximately the same by the (He\(^3\), p) and (\(\alpha, d\)) reactions. This is expected if the \((d_\frac{5}{2})^2\) configuration attributed to this state is correct. Figure 34 shows the angular distribution of the protons from the (He\(^3\), p) transition to

---

*This trend is not too apparent when measurements are compared\(^3\) at bombarding energies lower than 15 MeV, but it becomes very definite when \(^{10}\text{B}(d, p)^{11}\) results\(^5^9\) at 28 MeV are compared with data\(^5^0\) at 7.8 MeV.
Table VI. Comparison of the energy levels of $^{14}\text{N}$ populated by the $(\alpha, d)$ and $(\text{He}^3, p)$ reactions.

<table>
<thead>
<tr>
<th>MeV</th>
<th>J</th>
<th>Level</th>
<th>T</th>
<th>Level intensity$^a$ (He$^3$, p)</th>
<th>(α, d)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>1</td>
<td>+</td>
<td>0</td>
<td>0.48 mb$^b$</td>
<td>0.8 mb$^d$</td>
</tr>
<tr>
<td>2.31</td>
<td>0</td>
<td>+</td>
<td>1</td>
<td>0.33 mb$^b$</td>
<td></td>
</tr>
<tr>
<td>3.95</td>
<td>1</td>
<td>+</td>
<td>0</td>
<td>0.44 mb$^b$</td>
<td>0.36 mb$^e$</td>
</tr>
<tr>
<td>4.91</td>
<td>0</td>
<td>-</td>
<td>0</td>
<td>Strong</td>
<td></td>
</tr>
<tr>
<td>5.10</td>
<td>2</td>
<td>-</td>
<td>0</td>
<td></td>
<td></td>
</tr>
<tr>
<td>5.69</td>
<td>1</td>
<td>-</td>
<td>0</td>
<td></td>
<td>Strong</td>
</tr>
<tr>
<td>5.83</td>
<td>3</td>
<td>-</td>
<td>0</td>
<td></td>
<td></td>
</tr>
<tr>
<td>6.21</td>
<td>1</td>
<td>+</td>
<td>0</td>
<td></td>
<td></td>
</tr>
<tr>
<td>6.44</td>
<td>3</td>
<td>+</td>
<td>0</td>
<td>Strong</td>
<td>Strong</td>
</tr>
<tr>
<td>7.03</td>
<td>2</td>
<td>+</td>
<td>0</td>
<td>g Weak</td>
<td></td>
</tr>
<tr>
<td>7.97</td>
<td>2</td>
<td>-</td>
<td>0</td>
<td>g Weak</td>
<td></td>
</tr>
<tr>
<td>8.47</td>
<td>5</td>
<td>+</td>
<td>0</td>
<td>5 mb$^h$</td>
<td>7 mb$^h$</td>
</tr>
<tr>
<td>9.41</td>
<td>1</td>
<td>-</td>
<td>0</td>
<td>g Strong</td>
<td></td>
</tr>
</tbody>
</table>

$^a$The numbers are in mb/sr without taking the weighting factor $2J + 1$ into account.

$^b$Range of integration from 9 1/2 to 157° lab.

$^c$Range of integration from 10 to 133° lab.

$^d$Not observed.

$^e$Range of integration from 10° to 90° lab.

$^f$Do not seem to be made strong but could be obscured by the neighboring peak since the energy resolution was never better than 700 keV.

$^g$Obscured by neighboring levels.

$^h$Range of integration from 20.4° to 78.2°.
Fig. 34. Angular distribution of proton from formation of the 9.0-MeV level of N\textsuperscript{14} by the Cl\textsuperscript{2}(He\textsuperscript{3}, p)N\textsuperscript{14} reaction.
the 9.0-MeV level. The forward-peaking angular distribution resembles closely the one of the deuteron from the \((\alpha, \, d)\) reaction. The ratio of the cross section of the 9.0-MeV level relative to the ground-state cross section is larger for the \((\text{He}^3, \, p)\) reaction. It should be noted that other states are included in the angular distributions of the 9.0-MeV level and more levels are allowed in the \((\text{He}^3, \, p)\) transition.

The similarity in the shape of the angular distribution of the \((d_{5/2})^2\) levels formed by the \((\text{He}^3, \, p)\) and the \((\alpha, \, d)\) reactions was also noticed in the case of the \(0^{16}(\text{He}^3, \, p)^{18}\) transition to the 1.1-MeV level.

The \(0^{16}(\text{He}^3, \, p)^{18}\) reaction was briefly investigated using the same experimental procedure described for the \(C^{12}\) target. The reaction was observed over the angular range from 10° to 60° lab. Figure 35 shows the proton energy spectrum observed at 25° lab. Figure 36 presents the angular distribution of the 1.1-MeV level of \(F^{18}\). No absolute value is available for the differential cross section of this transition, but the resemblance to the angular distribution of the \(0^{16}(\alpha, \, d)^{18}\) reaction to the same level (Fig. 18) is striking.

C. The \((\alpha, \, \alpha')\) Reaction

The \(N^{14}(\alpha, \, \alpha')N^{14}\) reaction was investigated to obtain additional support of the \((d_{5/2})^2\) assignment for the 9.0-MeV level of \(N^{14}\). However, other valuable results, obtained as a bonus in this investigation, are also mentioned. The elastic scattering of \(\alpha\) particles from the \(N^{14}\) nucleus has been widely investigated in the energy range from 15 to 40 MeV, but the excited levels were seldom observed.

The 48- and 65-MeV \(\alpha\) beams from the 60-inch and 88-inch cyclotrons, respectively, were used in the present work. The angular range of about 10° to 60° (lab) was studied in both cases. Figure 37
Fig. 35. Proton energy spectrum from the $^{16}\text{O}(\text{He}^3, p)^{18}\text{F}$ reaction observed at $25^\circ$ with $3.2$-MeV $\text{He}^3$ particles.
Fig. 36. Angular distribution of protons from formation of the 1.1-MeV level of $^{18}$F by the $^{16}$O($^{3}$He, p)$^{18}$F reaction.
Fig. 37. Alpha-particle energy spectrum from the $^14N(\alpha, \alpha')^14N$ reaction observed at $17^\circ$ (lab) with 65-MeV $\alpha$ particles.
presents the α-particle energy spectrum at 17° (lab) recorded at the 88-inch cyclotron. The energy resolution is 250 keV and the range of observation includes 11.8 MeV of excitation.

Figure 38 shows the angular distribution of the elastically scattered alphas at 47.4 and 65 MeV, as well as the results of Ploughe at 19 MeV and Yavin and Farwell at 40 MeV. At 65 MeV the diffraction pattern is very weak beyond 35° c.m., but the similarity both in shape and in absolute cross section is good at smaller angles. The forward scattering is well described by Blair in terms of the Fraunhofer black-disk cross section:

$$\frac{d\sigma}{d\Omega} = (KR_0^2/2) \left(\frac{J_1(X)}{(X)}\right)^2$$

in which $K$ is the incoming wave number, $R_0$ is the absorption radius, and $J_1$ is the first-order Bessel function of argument $X$. The parameter $X$ is defined as $X = KR_0\theta$ (or sometimes $2KR_0\sin\theta$), where $\theta$ is the scattering angle. The radii of interaction calculated from the black-disk model varied from 5.89 fermis at 19 MeV and 5.37 fermis at 40 MeV to 4.79 fermis at 47.4 MeV and 4.65 fermis at 65 MeV. The validity of the model seems to be maintained even in the relatively low-energy region of 19 MeV where the Fraunhofer approximation should start breaking down. The solid line of Fig. 39 represents the Blair model fits to the 48- and 65-MeV elastic-scattering data.

The forbidden 2.31-MeV level was not seen at either 47.4 or 65 MeV. The absence of formation at this level was also noticed at 31.5 and 22 MeV. Although at 19.2 MeV it was reported to be weakly excited, no upper limit was set. The absence of inelastic scattering data measured below 18 MeV is unfortunate since this is the bombarding energy leading to the energy of excitation of the $^{18}$F nucleus set by Wilkinson and Lane and Thomas as the upper limit for the isospin admixture to take place in the compound state. Such
Fig. 38. Angular distributions of elastically scattered $\alpha$ particles from $^{14}N$ at:

- $19.1$ MeV (see Ref. 61)
- $40.0$ MeV (see Ref. 63)
- $47.4$ MeV (this experiment)
- $65.0$ MeV (this experiment)
Fig. 39. Angular distributions of elastically scattered alpha particles from $^14N$ at 47.4 MeV (○) and 65.0 MeV (□). The solid line is the angular distribution predicted from the black-disk model at these energies.
a region of strong admixture has been experimentally found in the $^{16}(d, \alpha)^{14}N$ investigation.\textsuperscript{68}

The \textit{(p$_{3/2}$)}$^{7} (p_{1/2})^{3}$ levels at $3.95$ and $7.03$ MeV were both observed in the present work. The formation of these levels is possible by a single-nucleon promotion from the \textit{(p$_{3/2}$)}$^{8} (p_{1/2})^{2}$ ground state of $^{14}N$. The other excited states observed at $4.91, 5.11, 5.69, 5.83, 7.97, 8.47, \text{ and } 9.41$ MeV all have a $p_{1/2}$ component and can thus be accounted for by single-nucleon promotion. Figure 40 shows the angular distributions of the $3.95, 4.91 + 5.10, 5.69 + 5.83$, and $7.03$ MeV levels observed at a bombarding of $47.4$ MeV.

The arrow in Fig. 37 indicates the position of the \textit{(d$_{5/2}$)}$^{2}$ level. This level should not be made by single-nucleon promotion and was not observed in the $^{14}(\alpha, \alpha')^{14}N$ investigation. The \textit{(s$_{1/2}$ d$_{5/2}$)}$^{2}$ and \textit{(s$_{1/2}$)}$^{2}$ levels at $6.44$ and $6.21$ MeV would also require double-nucleon promotion and are not observed.

The $^{16}(\alpha, \alpha')^{16}$ reaction was also studied to confirm the \textit{(d$_{5/2}$)}$^{5}$ assignments of the levels highly populated by the $^{14}(\alpha, d)^{16}$ reaction. The results of this investigation indicated that a $4^{+}$ level was definitely identified at $14.98$ MeV and could possibly be the \textit{(d$_{5/2}$)}$^{2}$ level previously reported at $14.7$ MeV. The reaction, however, did not seem to populate the $16.2$-MeV level, which is another of the three levels of \textit{(d$_{5/2}$)}$^{2}$ character. Unfortunately the peak corresponding to the $16.2$-MeV level would fall very close to the He$^{3}$ peak from the $^{16}(\alpha, \text{He}^{3})^{15}$ reaction, but the width of the He$^{3}$ peak does not indicate any interference from another level. The $14.98$-MeV level could possibly be the \textit{(d$_{5/2}$)}$^{2}$ level since the $J = 4$ state could be mixed with other configurations e.g.,

$$\Psi_{4+} = a \left[ (N^{14}) J + (d_{5/2})^{2} \right]_{4} + b \left[ (N^{14}) J' + (d_{5/2})^{2} \right]_{4} + \ldots$$
Fig. 40. Angular distribution of α particles from the $^{14}\text{N}(\alpha, \alpha')^{14}\text{N}$ reaction to the 3.95-MeV (△), 7.03-MeV (○), (4.9 + 5.1)-MeV (△), and (5.7 + 5.8)-MeV (□) levels.
However the $J = 6$ level can be made only from

\[ \psi_{6^+} = 1.00 \left[ (N^{14})_{\frac{1}{2}} + (d_{5/2})_{\frac{3}{2}} \right]_6 \]

and should not be formed by the $(\alpha, \alpha)$ reaction.

Other valuable results of the $^{16}(\alpha, \alpha)^{16}$ investigation have been previously published in detail and are not repeated here.\(^{69}\)
IV. DISCUSSION

A. Identification of Highly Populated Levels of the $\left(\frac{5}{2}^+\right)^2_3$ and $\left(\frac{7}{2}^+\right)^2_7$ Configurations

1. Qualitative Discussion

For all the target nuclei studied by the (α, d) and (He$^3$, p) reactions (Secs. III. A and III. B), the energy spectra were dominated by one or more strongly populated levels. In a direct process involving the capture of a proton and a neutron, it is reasonable to expect that the levels formed in high yields will be those representable in $J$-$J$ coupling shell-model language as

$$\left[ J_T + (J_p J_n) J' \right] J$$

In this representation the angular momentum of the proton $J_p$ and of the neutron $J_n$ are vectorially added to $J'$, the angular momentum brought into the nucleus by the captured pair. $J'$ in turn is coupled to the angular momentum of the target $J_T$ to give $J$, the spin of the final state of the recoil nucleus. It is assumed that the configuration of the target core is unchanged in the reaction. This simple model does not allow the formation of core excited states. In a direct stripping reaction they should be populated only in much lower yield.

The shell-model assignment of $J_p$ and $J_n$ is thus one of the main concerns of this investigation. The first evidence that all the strongly populated levels might be of similar configuration was obtained when the Q values for their formation were plotted as a function of the mass number $A$ of the product nucleus. As Fig. 41 shows, the negative Q values decrease regularly as $A$ increases. The trend indicates that the subshell involved in the pair capture becomes closer and closer to the most stable configuration for the final nucleus.
Fig. 41. Relationship between the recoil-nucleus atomic mass number and the $Q$ value of formation of the levels preferentially populated by the $(\alpha, d)$ reaction. ○, $(d_{5/2})^2$ levels; ● $(f_{7/2})^2$
In the lighter targets, the highly populated peaks fall at only 1.1-MeV excitation in F\textsuperscript{18} and at the ground state in Al\textsuperscript{26} (both known 5+ levels), thus strongly suggesting that the capture is taking place in the d\textsubscript{5/2} shell. For the levels corresponding to the upper section of Fig. 37, the highly populated states are located at high excitation energy for the lighter targets but at only 0.60-MeV excitation in the Sc\textsuperscript{42} nucleus. Calcium-40 is a closed-shell nucleus and the next nuclei should then start filling the f\textsubscript{7/2} shell. Thus the evidence is strong that the highly populated levels arise from the capture of a neutron-proton pair in either the d\textsubscript{5/2} or the f\textsubscript{7/2} shell.

This information obtained about J\textsubscript{p} and J\textsubscript{n}, the important value of J' is left to be assigned in the (J\textsubscript{p} J\textsubscript{n}) model. At this point the discussion is concerned only with the dynamics of the reaction; further evidence based on already known or predicted angular-momentum values for these levels is summarized later.

The selectivity of the reaction in populating a level of configuration (J\textsubscript{p} J\textsubscript{n})\textsubscript{J}, will depend in part on the degree to which the transferred nucleons are correlated in the nucleus; such correlation can be imposed by the angular-momentum coupling.\textsuperscript{70} The classical orbits of the two nucleons J\textsubscript{p} and J\textsubscript{n} are coplanar if J' is zero or has its maximum value. In other words, the motion of the two nucleons is spatially more correlated when the vector sum of the orbital angular momenta is either a minimum or a maximum. From a classical picture the vector sum 0 would imply that the two nucleons are going around the core in opposite directions. The only stripping process available would be a head-on collision with the nucleus. Such a mechanism would involve a large amount of absorption and thus would not be favored by a direct reaction. On the other hand, the transfer of the maximum value of L (L = 4 for the (d\textsubscript{5/2})\textsuperscript{2} levels and L = 6 for the (f\textsubscript{7/2})\textsuperscript{2} levels), which requires a grazing collision at the surface of the nucleus, is highly favored in a stripping mechanism. The captured nucleons go around the core in the same direction looking as
much as possible like a deuteron. Thus the correlation of the two nucleons in the recoil nucleus have a large overlap with the correlation possessed by the two nucleons in the light particle, causing an unusually strong transition.

The captured proton-neutron pair must be in its triplet state since the spinless \( \alpha \) particle is pictured as being broken into two deuterons, the captured and outgoing deuterons. The reaction will then favor the \((d_{5/2})^2\) and \((f_{7/2})^2\) configurations with the biggest \(3G\) and \(3I\) components—this is obviously the \((d_{5/2})^2\) and \((f_{7/2})^2\) configurations. The amplitudes of the possible L-S components of \((d_{5/2})^2\) and \((f_{7/2})^2\) configurations (obtained by expansion of the \(J-J\) wave functions) are summarized in Table VII. The spin-5 and spin-7 levels are the only ones with strong \(3G\) and \(3I\) components. Thus the levels of

\[
\left[J_T + (d_{5/2})^2\right]J \quad \text{and} \quad \left[J_T + (f_{7/2})^2\right]J
\]

configuration will be preferentially populated.

2. The Glendenning Two-Nucleon Stripping Theory

The qualitative argument in favor of the preferential population of maximum-spin levels, presented above, has been quantitatively treated by Glendenning \(^7\) for the \((d_{5/2})^2\) levels of \(N^{14}\). The differential cross section for two-nucleon stripping reactions can be written

\[
\frac{d\sigma}{d\Omega} \propto \frac{K_{\text{out}}}{K_{\text{in}}} \frac{2J_f + 1}{2J_i + 1} \sum_{LSJM} \frac{b_8^2}{2S+1} |\Sigma N_{NLSJ} M_{NL}|^2
\]

(2)

where \(K_{\text{in}}\) and \(K_{\text{out}}\) are the wave numbers for relative motion in the initial and final states; \(J_f\) and \(J_i\) are the spins of the final and initial states; the sum \(LSJM\) is over the orbital spin and
Table VII. J-J wave function

a. For \((\alpha_{5/2})^2\) configurations

<table>
<thead>
<tr>
<th>Level spin</th>
<th>L-S components</th>
</tr>
</thead>
<tbody>
<tr>
<td>5</td>
<td>(1.00 \ 3_G)</td>
</tr>
<tr>
<td>4</td>
<td>(\sqrt{\frac{4}{5}} \ 3_F + \sqrt{\frac{1}{5}} \ 1_G)</td>
</tr>
<tr>
<td>3</td>
<td>(\sqrt{\frac{108}{175}} \ 3_D - \sqrt{\frac{4}{175}} \ 3_G + \sqrt{\frac{63}{175}} \ 1_F)</td>
</tr>
<tr>
<td>2</td>
<td>(\sqrt{\frac{56}{125}} \ 3_P - \sqrt{\frac{9}{125}} \ 3_F + \sqrt{\frac{60}{125}} \ 1_D)</td>
</tr>
<tr>
<td>1</td>
<td>(\sqrt{\frac{7}{25}} \ 3_S - \sqrt{\frac{4}{25}} \ 3_D + \sqrt{\frac{14}{25}} \ 1_P)</td>
</tr>
<tr>
<td>0</td>
<td>(-\sqrt{\frac{2}{5}} \ 3_P + \sqrt{\frac{3}{5}} \ 1_S)</td>
</tr>
</tbody>
</table>

b. For \((f_{7/2})^2\) configurations

<table>
<thead>
<tr>
<th>Level spin</th>
<th>L-S components</th>
</tr>
</thead>
<tbody>
<tr>
<td>7</td>
<td>(1.00 \ 3_I)</td>
</tr>
<tr>
<td>6</td>
<td>(\sqrt{\frac{42}{49}} \ 3_H + \sqrt{\frac{7}{49}} \ 1_I)</td>
</tr>
<tr>
<td>5</td>
<td>(-\sqrt{\frac{6}{539}} \ 3_I + \sqrt{\frac{390}{539}} \ 3_G + \sqrt{\frac{143}{539}} \ 1_H)</td>
</tr>
<tr>
<td>4</td>
<td>(-\sqrt{\frac{5}{147}} \ 3_H + \sqrt{\frac{88}{147}} \ 3_F + \sqrt{\frac{54}{147}} \ 1_G)</td>
</tr>
<tr>
<td>3</td>
<td>(-\sqrt{\frac{24}{343}} \ 3_G + \sqrt{\frac{165}{343}} \ 3_D + \sqrt{\frac{154}{343}} \ 1_F)</td>
</tr>
</tbody>
</table>
Table VII. Continued

<table>
<thead>
<tr>
<th></th>
<th>(-\sqrt{\frac{6}{49}}) 3(_F) + \sqrt{\frac{18}{49}} 3(_P) + \sqrt{\frac{25}{49}} 1(_D)</th>
<th>(-\sqrt{\frac{10}{49}}) 3(_D) + \sqrt{\frac{12}{49}} 3(_S) + \sqrt{\frac{27}{49}} 1(_P)</th>
<th>(-\sqrt{\frac{3}{7}}) 3(_P) + \sqrt{\frac{4}{7}} 1(_S)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
total angular momenta of the transferred pair; the amplitude \( b_s \) measures the amount of spin state \( s \) (0 or 1) of the stripped pair that is present in the lighter nuclide from which they have been stripped; the quantity \( M_{NL} \) is the amplitude for the absorption of the pair of nucleons into a state where the c.m. motion is characterized by orbital angular momentum \( L \), with \( Z \) projection \( M \), and principal quantum number \( N \); and \( G_{NL3J} \), the quantity of interest at this point, refers to the structure of the nuclear states involved.

\( G_{NL3J} \) is a product of three overlap integrals:

\[
G_{NL3J} = \sum_{\gamma} \beta_{\gamma LSJ} F_n(n_0, NL; L|n_{11}, n_{22}; L)
\]

a. \( \beta_{\gamma LSJ} \)

The overlap integral \( \beta \) measures the degree to which the final state resembles the target-state vector coupled to the transferred nucleons that are in a state whose orbital, spin, and total angular momenta are \( L, S, \) and \( J \). The symbol \( \gamma \) stands collectively for the quantum numbers describing the state of the transferred nucleons in the final nucleus. For the \( C^{12}(\alpha, d)N^{14} \) reaction \( \beta_{LJS} \) can be represented in \( J-J \) coupling by

\[
\beta_{LJS} = \left[ 3(2L+1)(2J_1+1)(2J_2+1) \right]^{1/2} \left( \begin{array}{c} l_1 \ 1/2 \ \gamma_1 \\ l_2 \ 1/2 \ \gamma_2 \\ L \ I \ J \end{array} \right)
\]

b. \( F_n \)

The overlap integral \( F_n \) is concerned with the relative motion of the stripped nucleons in their original state in the incident nuclide and their final state in the nucleus. This overlap integral can be calculated explicitly when harmonic oscillator functions are used. For the \( (\alpha, d) \) reactions, \( F_n \) becomes
\[ F_n = \frac{\sqrt{(2n-1)!}}{2^{n-1}(n-1)!} (xy)^{3/2} (1-x)^{n-1} , \]

where \( x = \frac{2\nu}{8\eta^2 + \nu} \), \( y = 2\eta \sqrt{\frac{2}{\nu}} \), and \( n = 1, 2 \ldots \).

The size parameter \( \eta \) is related to the rms radius as follows for the \( \alpha \) particle:

\[ \eta^2 = \frac{9}{64 \langle r^2 \rangle} . \]

The harmonic-oscillator parameter \( \nu \) is empirically defined as: \( \nu = 0.155 \sqrt{V/R} \), where \( V \) is the Woods-Saxon well depth and \( R \) is its radius at half value (1.3A \( ^{1/3} \)).

c. \( \langle n_0, NL; L|n_1 l_1 , n_2 l_2 ; L \rangle \)

This bracket represents the amplitude for relative \( S \) motion in the nuclear state in which the individual nucleons are in orbits \( n_1 l_1 \) and \( n_2 l_2 \) with total orbital angular momentum \( L \). The numerical values of the transformation brackets are directly available.

The numerical calculation of \( G_{NLJ}^{\alpha} \) was carried out by Glendenning\(^7\) for the \( (d_5/2)^2 \) levels of \( N^+ \). Table VIII reproduces his results for \( J = 5, 3, \) and 1, together with the other relevant quantities.

The differential cross section for the \( (d_5/2)^2 \) levels can thus be compared by the introduction of the numerical values of the nuclear structure factor \( G_{NLJ}^{\alpha} \) in Eq. (2).

\[ \left( \frac{d\sigma}{d\Omega} \right)_J = 5 \times 11 \sum_M |0.587 B_{14}^M|^2 \]
Table VIII. Spectroscopic data for \((d_{5/2})^2\) \(T = 0\) states

<table>
<thead>
<tr>
<th>(J)</th>
<th>(L)</th>
<th>(L-J)</th>
<th>(N)</th>
<th>(n)</th>
<th>(F_n)</th>
<th>(\langle 1 \rangle^a)</th>
<th>(G_{NLIJ})</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0</td>
<td>0.529</td>
<td>3</td>
<td>1</td>
<td>0.959</td>
<td>0.408</td>
<td>0.266</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>0.785</td>
<td>2</td>
<td>1</td>
<td>0.959</td>
<td>0.289</td>
<td>0.218</td>
</tr>
<tr>
<td></td>
<td>1</td>
<td>0.959</td>
<td>2</td>
<td>2</td>
<td>0.274</td>
<td>-0.441</td>
<td>-0.095</td>
</tr>
<tr>
<td>2</td>
<td>1</td>
<td>0.4</td>
<td>1</td>
<td>1</td>
<td>0.071</td>
<td>0.408</td>
<td>0.0153</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>0.071</td>
<td>1</td>
<td>2</td>
<td>0.274</td>
<td>-0.441</td>
<td>-0.0484</td>
</tr>
<tr>
<td>3</td>
<td>4</td>
<td>-0.151</td>
<td>1</td>
<td>1</td>
<td>0.959</td>
<td>0.612</td>
<td>0.587</td>
</tr>
</tbody>
</table>

\(^a\)Symbol used for the transformation integral.
\[ \frac{\partial \sigma}{\partial \Omega} \bigg|_{J = 3} \approx 7 \left\{ \sum_{M} \left| 0.218 B_{22}^{M} - 0.095 B_{12}^{M} \right|^2 + \sum_{M} \left| 0.089 B_{14}^{M} \right|^2 \right\} \]

\[ \frac{\partial \sigma}{\partial \Omega} \bigg|_{J = 1} \approx 3 \left\{ \sum_{M} \left| 0.206 B_{30}^{0} - 0.108 B_{20}^{0} + 0.015 B_{10}^{0} \right|^2 + \sum_{M} \left| 0.111 B_{22}^{M} - 0.048 B_{12}^{M} \right|^2 \right\} . \]

The ratio \( \frac{K_{\text{out}}}{K_{\text{in}}} \) is neglected here, although it would be slightly different for the various values of \( J \), since the excitation energy of these levels would not be the same. A further approximation leads to these simplified equations:

\[ \frac{\partial \sigma}{\partial \Omega} \bigg|_{J = 5} \approx 3.8 |B_4|^2 \]

\[ \frac{\partial \sigma}{\partial \Omega} \bigg|_{J = 3} \approx 0.056 |B_4|^2 + 0.105 |B_2|^2 \]

\[ \frac{\partial \sigma}{\partial \Omega} \bigg|_{J = 1} \approx 0.012 |B_2|^2 + 0.039 |B_0|^2 . \]

Since the forward-peaking character of the angular distribution of these levels indicates a grazing collision at large radius, and since it is assumed that contributions from the interior are suppressed by absorption, the following inequality is justified:

\[ |B_4|^2 \geq |B_2|^2 \geq |B_0|^2 . \]  \hspace{1cm} (3)
This quantitative treatment shows that the $J = 5$ level will be populated at least $2^4$ times as much as the $J = 3$ level, and the latter more than the $J = 1$ level. Although the calculation does not rely on an actual value of the transfer probability $E_{NL}^M$, the $J = 5$ level is so highly favored that the inequality (3) will not affect the above conclusion.

B. Angular Distributions of the $(d_{5/2})_5^2$ and $(f_{7/2})_7^2$ levels

The connection existing between the angular distribution of the outgoing particle and the value of $L$, the angular momentum transferred in the reaction, was first classically demonstrated by Butler for the single-nucleon stripping reaction, and has been widely verified ever since. It is thus not surprising that the gross structure levels that are formed by an identical mechanism and involve high values of $L$ (4 or 6) present similar angular distributions. Figure 42 shows the angular distributions of the levels assigned a $(d_{5/2})_5^2$ or $(f_{7/2})_7^2$ configuration during the present investigation.

The shape of the angular distributions is very forward peaked, and in all cases the cross section decreases monotonically with angle. Such a behavior can be explained in terms of increasing momentum mismatch at larger angles. A semiclassical treatment of the single-nucleon stripping reaction by Butler describes very well how the angular distribution of a transition is affected by the momentum transfer involved.

It is assumed first that the core will absorb any particle hitting the nucleus within a certain radius to form a compound nucleus. The absorbed particles are thus lost for a direct process that takes its contribution exclusively from particles coming with partial waves large enough to give a grazing collision. This model is especially valid for the gross structure levels whose preferential population (very large at small angle) indicates their grazing-collision character (Sec. IV. A. 1). The $\alpha$ particle has a linear momentum $K_\alpha$.
Fig. 42. Angular distribution of the levels preferentially populated by the (α, d) reaction:

- 9.0-MeV level of N\textsuperscript{14}
- 14.7-MeV level of O\textsuperscript{16}
- 16.2-MeV level of O\textsuperscript{16}
- 7.6-MeV level of C\textsuperscript{17}
- 9.0-MeV level of C\textsuperscript{17}
- 1.1-MeV level of F\textsuperscript{18}
- 1.53-MeV level of Na\textsuperscript{22}
- 7.46-MeV level of Na\textsuperscript{22}
- 1.87-MeV level of K\textsuperscript{42}
- 0.60-MeV level of Sc\textsuperscript{42}.

Was multiplied by 10
for a particular state the outgoing deuteron has a linear momentum $K_d$. The amount of momentum transferred in the reaction $Q_n$ is thus the vector difference

$$Q_n = (\hbar K_\alpha - \frac{M_T}{M_f} \hbar K_d)$$

where $M_T$ and $M_f$ are the masses of the target and final nuclei. The following vector diagram illustrates how $Q$ increases with the scattering angle $\theta$:

Classically the angular momentum carried into the nucleus by the captured particle is represented by the product $Q\alpha p$, where $p$, the impact parameter, can range from 0 to $R$ (the interaction radius); the maximum value of angular momentum available will be $\hbar QR$.

For the reaction to proceed it is required that enough angular momentum be available for the transition. More precisely, the inequality

$$(K_\alpha - \frac{M_T}{M_f} K_d) R \geq L$$

must be satisfied. Obviously, if at small angles there is not enough angular momentum available to satisfy inequality (4), the angular distribution will be at a maximum at the angle where $(K_\alpha - \frac{M_T}{M_f} K_d) R$ is equal to $L$. However if inequality (4) is already satisfied at small angles, the angular distribution will be forward peaking since the incoming particle will prefer to split in such a way that $K_d$ is
close to the direction of $K_\alpha$. The angular distribution would thus be expected to fall off with angle as the momentum mismatch between $K_R-L$ and $[M_t/M_f] K_d R$ increases monotonically.

For the levels of $(d_{5/2})_5^2$ and $(f_{7/2})_7^2$ configuration, the momentum transfer $QR$ has been calculated (by means of the program KINEMAT$^{73}$) and is shown in Figs. 43 and 44. The radius of interaction was defined as $R = (1.3 A^{1/3} + 1.5)$. These figures show that for all cases inequality (4) is satisfied at small angles for $L$ values of 4 and 6 and that the momentum mismatch

$$[K_R - \frac{M_t}{M_f} K_d R - L]$$

is very similar for all the gross structure levels. For the $(d_{5/2})_5^2$ levels, the mismatch goes from 2 units at $10^\circ$ to about 4 at $40^\circ$. In the case of the $(f_{7/2})_7^2$ levels, the mismatch goes from 1.1 to 3.8 over the same range. This consideration agrees with the fact that the angular distributions of all the levels shown in Fig. 38 fall off at about the same rate.

It would be interesting to observed these high $L$ transitions at a bombarding energy where inequality (4) is not satisfied at small angles. It would then be possible to identify the point where enough angular momentum is available, and thus obtain additional proof of the spin assignment of the final states.

Such a possibility was investigated but the kinematics of the ($\alpha$, d) reaction to the giant levels is such that inequality (4) is satisfied when the bombarding energy is high enough to overcome the threshold value of the reaction as shown in Fig. 45. The calculation shown was performed for the 1.1-MeV level of $^{18}_8 F$ with a 4.78 $f$ radius of interaction.

However a similar calculation with the ($He^3$, p) reaction showed that insufficient angular momentum at small angles is available with low bombarding energy for the $^{16}_2 (He^3, p)^{18}_8 F$ transition to the 1.1-MeV
Angular dependence of \( Q_R \) from the kinematics of the \((\alpha, d)\) reaction to the \( (d_{5/2})^2 \) levels:

- \( \cdots \ldots \ldots \) 9.0-MeV level of \( N^{14} \)
- \( \cdots \ldots \ldots \) 14.7-MeV level of \( O^{16} \)
- \( \cdots \cdots \cdots \) 16.2-MeV level of \( O^{16} \)
- \( \cdots \cdots \cdots \) 7.6-MeV level of \( O^{17} \)
- \( \cdots \cdots \cdots \) 9.0-MeV level of \( O^{17} \)
- \( \cdots \cdots \cdots \) 1.1-MeV level of \( F^{18} \)
- \( \cdots \cdots \cdots \) 1.53-MeV level of \( Na^{22} \).
Fig. 44. Angular dependence of QR from the kinematics of the (α, d) reaction to the \( (2^+ \, 7/2)_7 \) levels:

- \(-\) 7.46-MeV level of Na\(^{22}\)
- \(-\) 1.87-MeV level of K\(^{42}\)
- \(-\) 0.60-MeV level of Sc\(^{42}\).
Fig. 45. Angular dependence of $QR$ for the 1.1-MeV level of $^{18}\text{F}$ from $^{16}\text{O}(\alpha, d)^{18}\text{F}$ at various bombarding energies.
level. Figure 46 also illustrates that at the bombing energy of 31.2 MeV used in the (He$^3$, p) investigation described in this work, the momentum transfer was sufficient for the transition to proceed at the smallest angle of observation.

The $^0^{16}$(He$^3$, p)$^{18}_F$ reaction was previously observed$^{74}$ at bombarding energies of 5.9 and 9.2 MeV and the kinematics of the reaction at these energies do not allow the $L = 4$ transitions at small angles. Figure 47 shows the angular distribution of the 1.1-MeV level measured at these two bombarding energies. Both angular distributions indicate the presence of a maximum at a large angle where $QR = L$.

The angular distribution observed with a bombarding energy of 5.9 MeV has a maximum at about 85°, whereas the one obtained at 9.2 MeV has a maximum at 67°. Figure 46 shows that the position of these peaks corresponds to the point where 4 units of angular momentum are available for the transition. The exact value of 4 is achieved when interaction radii of 4.7 and 4.5 f are used at 5.9 and 9.2 MeV, respectively. The excellent agreement between the position of the maxima in the angular distributions and the required value of $L$ confirms indirectly the previous configuration assignments made throughout this investigation.
Fig. 46. Angular dependence of QR for the 1.1-MeV level of $^{18}$F from $^{16}$O($^{3}$He, p)$^{18}$F at various bombarding energies.
Fig. 47. Angular distribution of protons from formation of the 1.1 MeV of $^{18}$F by the $^{16}$O($^3$He, p)$^{18}$F reaction at bombarding energies of 5.9 MeV (○) and 9.2 MeV (●). The arrows indicate the angle where QR = L = 4 for an interaction radius of 4.78 fm.
C. Conclusions

Table IX summarizes the information about the highly populated levels to which \( \left[ J_T + \left( \frac{d_5}{2} \right)^2 \right] J \) or \( \left[ J_T + \left( \frac{f_7}{2} \right)^2 \right] J \) configurations have been assigned.

1. The 9.0-MeV Level of \(^{14}N\)

No 5+ level has been previously reported at this excitation energy. This is not surprising since this region was explored previously only by the \( ^{13}C(p, \gamma)^{14}N \) and \( ^{13}C(p, p)^{13}C \) reactions, and such a level could be made only by simultaneous promotion of the \( \frac{1}{2} \) neutron in \(^{13}C\) to the \( d_5 \) shell and capture of the incident proton in the same shell. Similarly the 9.0-MeV level was absent in the \( ^{14}N(\alpha, \alpha')^{14}N \) investigation (Sec. III. C), indicating again that it could not be formed by a single-nucleon promotion mechanism. A shell-model calculation by True predicted that a \( (d_5^2) \) level would lie at about 9 MeV; this is in perfect agreement with the excitation energy of the highly populated level.

2. The 7.6 and 9.0-MeV Levels of \(^{17}O\)

These two peaks have been assigned

\[
\left[ \frac{1}{2} + \left( \frac{d_2}{2} \right)^2 \right] \frac{11}{2} \quad \text{and} \quad \left[ \frac{1}{2} + \left( \frac{d_5}{2} \right)^2 \right] \frac{9}{2}
\]

configurations on the basis of their high population. No levels of spins \( \frac{9}{2} \) and \( \frac{11}{2} \) have been reported at those energies. A theoretical calculation by N. K. Glendenning, using a Serber force, predicted a splitting of 2.1 MeV between the two configurations, the \( \frac{11}{2} \) level lying lower. This value is in reasonable agreement with the 1.6-MeV splitting measured experimentally.
Table IX. The \( (d_{5/2})^2 \) and \( (f_{7/2})^2 \) levels identified in the \((\alpha, d)\) reaction.

<table>
<thead>
<tr>
<th>Final nucleus</th>
<th>Energy level (MeV)</th>
<th>Q value (MeV)</th>
<th>( J ) ( \Pi ) ( T )</th>
<th>Cross Section range (mb/sr)</th>
<th>Integration range (deg. c.m.)</th>
<th>Configuration</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>N(^{14})</td>
<td>9.0 ± 0.05</td>
<td>-22.6</td>
<td>5 + 0</td>
<td>7</td>
<td>20.4 - 78.2</td>
<td>( (d_{5/2})^2 )</td>
<td>See Sec. IV. C. 1</td>
</tr>
<tr>
<td>O(^{16})</td>
<td>14.7 ± 0.3</td>
<td>-17.8</td>
<td>(4) + 0</td>
<td>7.1</td>
<td>11.3 - 73.4</td>
<td>( (d_{5/2})^2 )</td>
<td></td>
</tr>
<tr>
<td></td>
<td>16.2 ± 0.3</td>
<td>-19.3</td>
<td>(5,6) + 0</td>
<td>5.2</td>
<td>11.5 - 74.0</td>
<td>( (d_{5/2})^2 )</td>
<td></td>
</tr>
<tr>
<td></td>
<td>(17.2)</td>
<td>(-20.3)</td>
<td>(5,6) + 0</td>
<td>*</td>
<td>*</td>
<td>*</td>
<td></td>
</tr>
<tr>
<td>O(^{17})</td>
<td>7.6 ± 0.2</td>
<td>-17.4</td>
<td>11/2 - 0</td>
<td>6.4</td>
<td>11.2 - 66.6</td>
<td>( (d_{5/2})^2 )</td>
<td>See Sec. IV. C. 2</td>
</tr>
<tr>
<td>F(^{18})</td>
<td>1.1 ± 0.1</td>
<td>-17.4</td>
<td>5 + 0</td>
<td>11.2</td>
<td>14.9 - 72.7</td>
<td>( (d_{5/2})^2 )</td>
<td>See Sec. IV. C. 3</td>
</tr>
<tr>
<td>Na(^{22})</td>
<td>1.53 ± 0.1</td>
<td>-14.1</td>
<td>(5 +) 0</td>
<td>2.1</td>
<td>11.7 - 60.5</td>
<td>( (d_{5/2})^2 )</td>
<td></td>
</tr>
<tr>
<td>Al(^{26})</td>
<td>0.0 ± 0.1</td>
<td>-12.4</td>
<td>5 + 0</td>
<td>*</td>
<td>*</td>
<td>( (d_{5/2})^2 )</td>
<td>See Sec. IV. C. 3</td>
</tr>
<tr>
<td>Na(^{22})</td>
<td>7.46 ± 0.2</td>
<td>-19.9</td>
<td>(7 +) 0</td>
<td>1.1</td>
<td>12.0 - 61.8</td>
<td>( (f_{7/2})^2 )</td>
<td></td>
</tr>
<tr>
<td>Al(^{26})</td>
<td>6.91 ± 0.3</td>
<td>-19.3</td>
<td>(7 +) 0</td>
<td>*</td>
<td>*</td>
<td>( (f_{7/2})^2 )</td>
<td>See Sec. IV. C. 4</td>
</tr>
<tr>
<td>Cl(^{34})</td>
<td>5.2 ± 0.3</td>
<td>-17.4</td>
<td>(7 +) 0</td>
<td>*</td>
<td>*</td>
<td>( (f_{7/2})^2 )</td>
<td></td>
</tr>
<tr>
<td>K(^{40})</td>
<td>1.87 ± 0.2</td>
<td>-12.7</td>
<td>(7 +) 0</td>
<td>1.6</td>
<td>11.6 - 53.8</td>
<td>( (f_{7/2})^2 )</td>
<td></td>
</tr>
<tr>
<td>Sc(^{42})</td>
<td>0.60 ± 0.1</td>
<td>-13.9</td>
<td>7 + 0</td>
<td>4.3</td>
<td>13.6 - 64.2</td>
<td>( (f_{7/2})^2 )</td>
<td>See Sec. IV. C. 5</td>
</tr>
</tbody>
</table>
3. **The 1.1-MeV Level of F\(^{18}\) and the Ground State of Al\(^{26}\)**

These two levels have already been assigned a spin and parity of 5+ from previous studies.\(^{27,43}\)

4. **The 6.91-MeV Level of Al\(^{26}\)**

The position of the \((f_{7/2})^2\) level in Al\(^{26}\) can be predicted from the single-nucleon levels reported for Al\(^{25}\). The Al\(^{25}\) nucleus has been well studied and the ground state is assigned \(^{43}\)a spin of \(5/2^+\) (very likely \(d_{5/2}\) configuration). The same reference shows a \(7/2^-\) level at 3.72 MeV. The Al\(^{26}\) ground state has a spin of 5+ and we believe it to have a \((d_{5/2})^2\) configuration. Using these two pieces of information, one can predict the \((f_{7/2})^2\) level of Al\(^{26}\) to be at 7.44 MeV (twice 3.72 MeV, neglecting the difference of the pairing energies in the \(d_{5/2}\) and \(f_{7/2}\) shells). The merit of this comparison rests, however, on the validity of the assignment of the \(d_{5/2}\) and \(f_{7/2}\) configurations to the ground state and 3.72-MeV level, respectively. The assignment of the \(d_{5/2}\) configuration is justified from simple shell-model consideration, but the \(7/2^-\) state is believed to belong to a rotational band in which the \(f_{7/2}\) configuration is only one of the components.\(^{76}\)

5. **The 0.60-MeV Level of Sc\(^{42}\)**

Decay studies have shown the presence of a low-lying isomer of Sc\(^{42}\) with a spin of 6+ or 7+ (probably 7+).\(^{77,78}\) Very likely this is the level identified at an excitation energy of 0.60 MeV in the \((\alpha, d)\) reaction.
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REFERENCES

16. G. Igo (Lawrence Radiation Laboratory, Berkeley, California) private communication, January 1964.
18. W. L. Hansen (Lawrence Radiation Laboratory, Berkeley, California) private communication to J. H. Elliott, (Lawrence Radiation Laboratory, Berkeley, California).
26. The computer program was written and made available by A. Springer (Lawrence Radiation Laboratory, Berkeley, California).
37. J. Aguilar, private communication to B. G. Harvey (Lawrence Radiation Laboratory) to E. Rivet, February 1964.
43. P. M. Endt and C. Van Der Leun, Nucl. Phys. 34, 1, (1962).
44. B. F. Bayman, Princeton University, private communication to B. G. Harvey (Lawrence Radiation Laboratory), June 1963.
56. N. K. Glendenning (Lawrence Radiation Laboratory, Berkeley, California) private communication to J. Cerny (Lawrence Radiation Laboratory) to E. Rivet, 1961.
58. R. J. Slobodrian, (Lawrence Radiation Laboratory, Berkeley, California) private communication, December 1963.
60. O. M. Bilaniuk and J. C. Hensel, Phys. Rev. 120, 211 (1960).
62. T. Mikumo, private communication to George Igo (Lawrence Radiation Laboratory, Berkeley, California) to E. Rivet, May 1963.
71. N. K. Glendenning, private communication and in Nuclear Spectroscopy with Direct Reactions, Chicago 1964, Argonne National Laboratory report ANL-6848, p. 188.
73. This computer program was written and made available by R. H. Pehl (Lawrence Radiation Laboratory, Berkeley, California).
75. N. K. Glendenning, (Lawrence Radiation Laboratory, Berkeley, California) private communication, January 1964.
76. H. Mang, (Lawrence Radiation Laboratory, Berkeley, California) private communication, February 1964.
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