(d,p) Reactions from Carbon, Nitrogen, and Oxygen*†

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Proton groups from the deuteron bombardment of thin targets of Formvar, polyethylene, and nylon have been analyzed by magnetic deflection in a 180-degree spectrograph and at 90 degrees to the incident beam. The MIT–ONR electrostatic generator was used to provide a deuteron beam at several energies ranging from 5 to 8.5 Mev. A total of twenty-eight individual proton groups has been observed. On the basis of both the relative intensities from the different targets and the differential energy shift, all the groups were identified with levels in C^{13}, C^{14}, N^{15}, or O^{17}. The present investigation covers the region of excitation up to energies corresponding approximately to the neutron binding energy in each of these nuclei. The results confirm previous knowledge of four proton groups from the $C^{12}(d,p)C^{13}$ reaction; two groups from $C^{13}(d,p)C^{14}$; seven groups from $N^{14}(d,p)N^{15}$; and four groups from $O^{16}(d,p)O^{17}$. In addition, eleven new particle groups were observed, two arising from the $C^{13}(d,p)C^{14}$ reaction and corresponding to energy levels in C^{14} at 6.723 and 6.894 Mev, and the remaining nine groups from the $N^{14}(d,p)N^{15}$ reaction and corresponding to levels in N^{15} at 7.575, 8.571, 9.062, 9.834, 10.069, 10.458, 10.544, 10.705, and 10.811 Mev.

I. INTRODUCTION

WITH energies up to 8.5 Mev available from the MIT–ONR electrostatic generator, it has become possible to study, with high resolution, (d,p) reactions on carbon, nitrogen, and oxygen, covering regions of excitation in the residual nuclei up to the neutron binding energy. The reactions of these light nuclei are of interest in themselves and are also important because these nuclei are present in backing materials and as contaminants on other targets. Hence, a knowledge of particle groups from these elements is essential for an analysis of the data taken with other target nuclei.

The present investigation has been confined to the analysis of the (d,p) groups leading to information on the excited states of C^{13}, C^{14}, N^{15}, and O^{17}. Alpha particles from (d,α) reactions were also observed but are not reported here. Earlier work in this Laboratory on these reactions, at bombarding energies of about 1.5 Mev, covered the excitation region from the ground state up to 3.4 Mev in C^{13},[1] 6.2 Mev in C^{14},[2] 8.4 Mev in N^{15},[3] and 2.9 Mev in O^{17}.[1] The information on C^{14} was mostly obtained in the course of bombardments of other target materials on which C^{13} was present only in its natural abundance. In addition, the excitation region between 5.1 and 6.2 Mev had been explored with targets in which the C^{13} content was enriched to 52 percent.[2] In the present work, these regions are now extended up to 4.9 Mev in C^{13}, 8.1 Mev in C^{14}, 10.8 Mev in N^{15}, and 4.1 Mev in O^{17}. A summary of the results from other workers on these nuclei may be found in the compilation of Ajzenberg and Lauritsen.[4]

The uncertainties in the present Q values are in general somewhat larger than those stated in previous work with this spectrograph. This is partly because of the higher bombarding energies used at present and is partly due to the fact that the results given here are compiled from many different runs on many targets, taken under varying conditions. As the main point of this investigation was the identification of the various proton groups, no great effort was made to increase the precision beyond that obtained in routine use of the spectrograph.

II. APPARATUS AND EXPERIMENTAL PROCEDURE

The experimental arrangement in connection with the MIT–ONR generator has been described in a recent paper.[5] Further details associated with the use of the 180-degree magnetic spectrograph and analysis of the data are treated in earlier publications.[1,2,6]

To aid in the identification of the target nucleus responsible for the various proton groups observed, three different target materials were used: Formvar, polyethylene, and nylon. A mass analysis of thin films of these targets was made by measuring the momenta of elastically scattered deuteron groups. The results showed that, aside from hydrogen and negligible amounts of sulfur and calcium or potassium, all three materials contained only carbon, nitrogen, and oxygen in varying proportions. The nylon targets were rich in all three elements; the Formvar targets contained carbon and oxygen with only traces of nitrogen; while polyethylene was predominantly carbon with traces of oxygen and nitrogen. By comparing the intensities of the individual proton groups when each target was

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† A portion of these results was presented at the 1953 Washington Meeting of the American Physical Society [Phys. Rev. **91**, 473 (1953)].

[1] Buechner, Strait, Sperduto, and Malm, Phys. Rev. **76**, 1543 (1949).

[2] Sperduto, Holland, Van Patter, and Buechner, Phys. Rev. **80**, 769 (1950).

[3] R. Malm and W. W. Buechner, Phys. Rev. **80**, 771 (1950).

[4] F. Ajzenberg and T. Lauritsen, Revs. Modern Phys. **24**, 321 (1952).

[5] Buechner, Sperduto, Browne, and Bockelman, Phys. Rev. **81**, 1502 (1953).

[6] Strait, Van Patter, Buechner, and Sperduto, Phys. Rev. **81**, 747 (1951).

bombarded with deuterons, it was possible to assign the group in question to the responsible nucleus. However, final identification was based on the differential energy shift observed when the incident deuteron energy was changed.

Thin films of Formvar were prepared in the usual manner[7] by dissolving the powder in dichloro-ethylene in the proportion of 4 grams of powder to 100 cc of solution. A small droplet of this solution was deposited on the surface of distilled water. After the dichloro-ethylene evaporated, the thin film of Formvar remaining on the surface was raised with a wire frame, $\frac{1}{2}$ in.$\times\frac{3}{4}$ in. Nylon targets were made by dissolving Type 8 nylon resin DV-55[8] in isopropyl alcohol. A thin film of the solution was allowed to flow onto a glass plate and, when dry, was stripped off under water. The film was then floated and picked up with a wire frame similar to that used with Formvar. Polyethylene targets were prepared in the same manner from a solution made by dissolving small polyethylene chips in warm xylene.

Self-supporting targets thus prepared could be made in thicknesses ranging from a few hundred to several thousand angstroms. A typical target used in these experiments had a thickness of approximately 5 kev for 5-Mev deuterons. Despite this small energy loss, these targets were incapable of withstanding beam currents of the order of 0.1 μa. With thin metallic layers, such as gold, supporting these films, the targets survived long exposures with beam currents as high as 0.3 μa. For this reason, most of the work was done with targets on which a thin layer of gold had been evaporated. Unfortunately, a low background of protons was observed which appeared to originate in the gold layer. The problem of preparing thin self-supporting targets remains a serious one.

III. ASSIGNMENT OF THE PROTON GROUPS

Figure 1 shows a typical momentum spectrum of the proton groups, observed at 90 degrees to the incident deuteron beam, obtained from a series of exposures at different field settings of the spectrograph, for a deuteron bombarding energy of 7.0 Mev. The upper plot shows the number of protons in a 0.5 mm$\times$18 mm strip of emulsion *vs* $H\rho$ for a Formvar target, while the lower plot gives the number of protons *vs* $H\rho$ when the target was nylon. A similar spectrum for a polyethylene target (not shown) appeared much like that from Formvar, except that the four oxygen peaks were appreciably reduced in height.

An examination of these plots shows clearly how, on the basis of intensity considerations alone, assignment of the target nucleus responsible for most of the peaks is a simple matter. All of the prominent proton groups from Formvar and polyethylene targets were identified with either carbon or oxygen; the additional prominent groups observed from nylon targets were attributed to nitrogen. The individual peaks in the figure are labeled with the symbol of the residual nucleus formed in the (d,p) reaction. The number above each peak refers to the excitation energy in Mev; for example, O^{17} 3.055 designates the particle group corresponding to the 3.055-Mev level in O^{17}. Each of the peaks appearing in Fig. 1 has been observed many times at several bombarding energies ranging from 5 to 8.5 Mev. For the range of masses of interest in this work, unambiguous assignment of a particular peak can generally be made from a measurement of the change in proton energy observed for a given change in deuteron energy. For the energy range available in the present work and an uncertainty in the energy measurements of the order of 0.1 percent, the uncertainty in the residual mass varies from about 0.25 amu to 0.4 amu for residual masses between 13 and 17.

Two new groups attributed to the $C^{13}(d,p)C^{14}$ reaction were assigned wholly on the basis of measurements from a voltage shift. These are discussed in Sec. IV below. In the momentum region shown in Fig. 1, a total of twenty-seven proton groups were assigned as follows: four to the $C^{12}(d,p)C^{13}$ reaction, three to the $C^{13}(d,p)C^{14}$ reaction, sixteen to the $N^{14}(d,p)N^{15}$ reaction, and four to the $O^{16}(d,p)O^{17}$ reaction. The region of excitation covered in each of the residual nuclei involved extends approximately up to the neutron binding energy in these nuclei. The positions of these neutron thresholds are indicated in Fig. 1. The sharp rise of the proton count just below $H\rho=270$ kilogauss-centimeters is caused by protons elastically scattered from the gold target backing. There is present with the atomic deuteron beam a small percentage of molecular hydrogen ions. These have nearly the same momentum as the deuterons, and, as a result of small variations in generator voltage, some pass through the slits and strike the target. Many of these are scattered from the target as protons of approximately half the energy of the incident deuterons. The momentum region below $H\rho=270$ is complicated, then, by the presence of scattered protons from the target nuclei in addition to the (d,p) groups. The region of excitation above the neutron binding is currently being investigated and will be reported at a later date.

IV. DISCUSSION OF RESULTS

The $C^{12}(d,p)C^{13}$ Reaction

The four groups attributed to this reaction have all been observed previously. The Q values determined from the present work are 2.717, -0.373, -0.967, and -1.138 Mev and the corresponding excitation energies in C^{13} are 3.090, 3.684, and 3.855 Mev. These values are in good agreement with previous measurements.[4] The probable errors in the measurement of the Q values for

[7] L. M. Fry and R. T. Overman, Atomic Energy Commission Report AECD-1800, 1948 (unpublished).

[8] The nylon resin was supplied by E. I. du Pont de Nemours and Company.

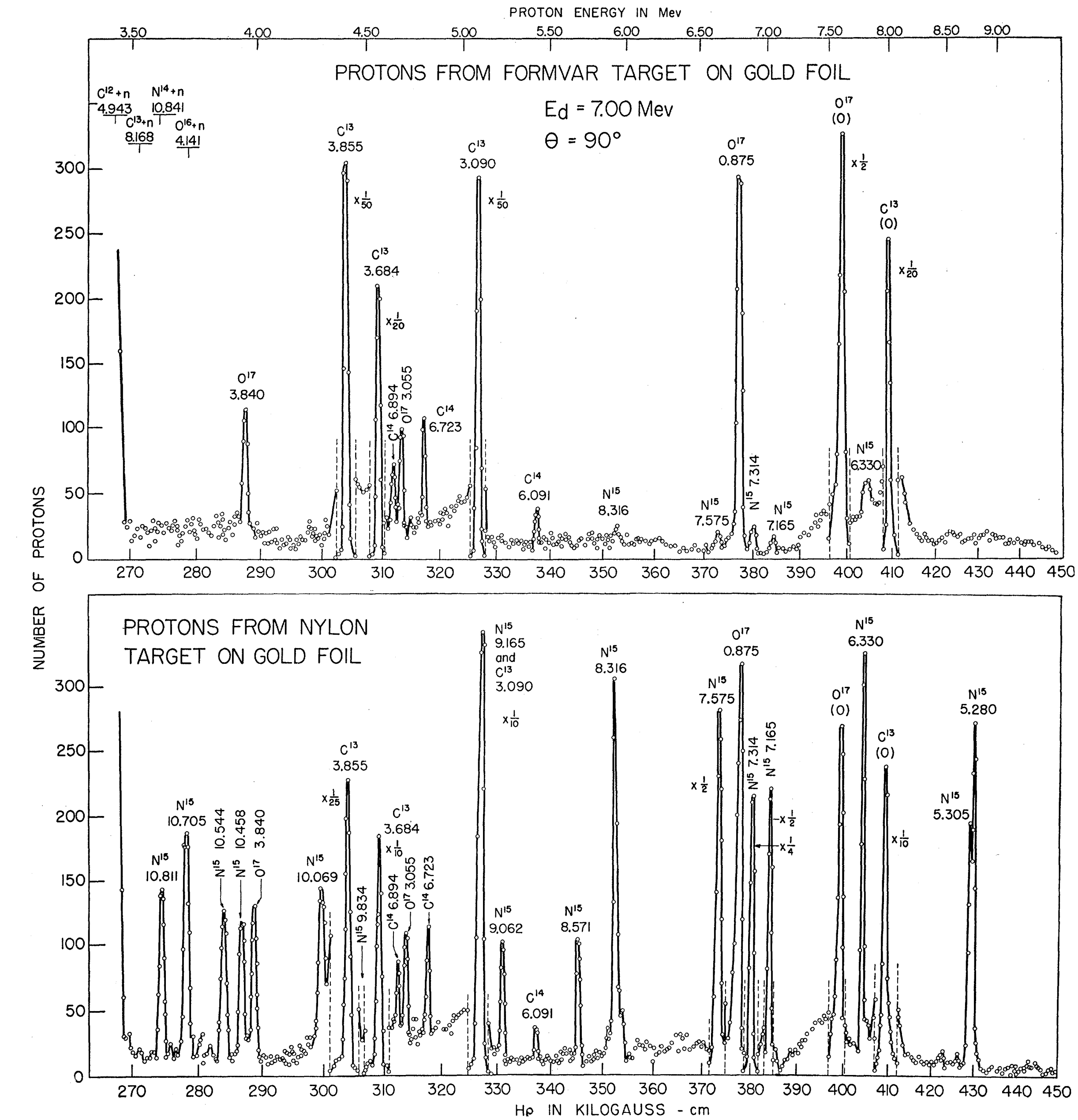

FIG. 1. Spectrum of proton groups from deuteron bombardment of Formvar and nylon targets.

this reaction range from 10 kev for the ground-state group to 7 kev for the 3.855 group. Our earlier measurement[6] at lower bombarding energy for the ground-state group was 2.716±0.005 Mev. In a number of cases where two adjacent particle groups are close enough in energy to be observed on the same plate, the separation can be measured to within a few kilovolts. Thus, the spacing between the 3.684- and 3.855-Mev levels has been determined as 170±3 kev. In the excitation region from the ground state up to 4.9 Mev in C^{13}, no other group has been observed with intensity greater than about 0.5 percent of the ground-state group. Proton groups corresponding to levels at 0.70 and 4.6 Mev reported[4] from the $B^{10}(\alpha,p)C^{13}$ reaction have not been observed. An energy-level diagram for C^{13} showing only the region investigated is presented in Fig. 2. The vertical arrows represent gamma-ray transitions that have been reported from the two reactions $C^{12}(n,\gamma)C^{13}$ and $C^{12}(d,p\gamma)C^{13}$. The observed gamma-ray energies are indicated along the vertical lines.

The two gamma-rays with energies of 4.948 and 3.68

Mev have been observed by Bartholomew and Kinsey[9] from slow neutron capture experiments, while the 3.082-Mev gamma has been reported by a number of workers[4] from the deuteron bombardment of C^{12}. No gamma ray that can be associated with the 3.855-Mev level has been reported.

The $C^{13}(d,p)C^{14}$ Reaction

Three of the four groups assigned to this reaction are shown in Fig. 1 at $H\rho = 313$, 318, and 337 kilogauss-centimeters, the ground-state group falling outside the range of the spectrograph at the 7.0-Mev bombarding energy. However, the latter group was observed at incident energies of 5.00, 5.16, and 5.65 Mev. From measurements at these energies, the ground-state Q value was determined to be 5.942 ± 0.011 Mev. This is in excellent agreement with the previous measurement[6] as is also the case for the first excited state, for which a Q value of -0.149 ± 0.007 Mev was found in the present work.

The two groups at $H\rho = 313$ and 318 kilogauss-centimeters have not been previously reported. It is clear from a comparison of the two spectra of Fig. 1 that nitrogen is not the target nucleus responsible for these groups. The assignment to C^{14} was made on the basis of results obtained at bombarding energies of 5.008 and 8.064 Mev. The expected change in proton energy over this range is (a) 2.396 Mev for a $C^{12}(d,p)C^{13}$ group; (b) 2.441 Mev for a $C^{13}(d,p)C^{14}$ group; and (c) 2.478 Mev for a $N^{14}(d,p)N^{15}$ group. The observed shift in energy was 2.436 ± 0.010 Mev.

The Q values determined from these measurements were -0.781 and -0.952 Mev, which correspond to levels in C^{14} at 6.723 and 6.894 Mev, respectively. The separation of the two new groups has been determined as 171 ± 3 kev. An energy-level diagram for C^{14} is shown in Fig. 2. The gamma-ray transitions shown here indicate the possible assignment of two gamma rays, among others, resulting from the deuteron bombardment of enriched C^{13} targets. The 6.11-Mev gamma was originally reported by Thomas and Lauritsen[10] and by others recently.[4] Mackin *et al.*[11] have reported a gamma ray of energy 6.730 ± 0.030 Mev. Bent *et al.*[12] also observed a 6.72-Mev gamma ray. This may well correspond to the 6.723-Mev level in C^{14} observed in our work. No gamma ray with an energy corresponding to the 6.894-Mev level has been reported. It should be noted here that all four groups have been observed from bombardment of the 1.1 percent C^{13} occurring in natural carbon. One measurement of the ground-state group was made with a KCN target enriched in C^{13}. The remaining survey on up through 8.1 Mev in C^{14} was explored only from bombardments of the natural carbon present on the various targets. The region below about 2-Mev excitation in C^{14} is not shown in Fig. 1 but was investigated at other bombarding energies between

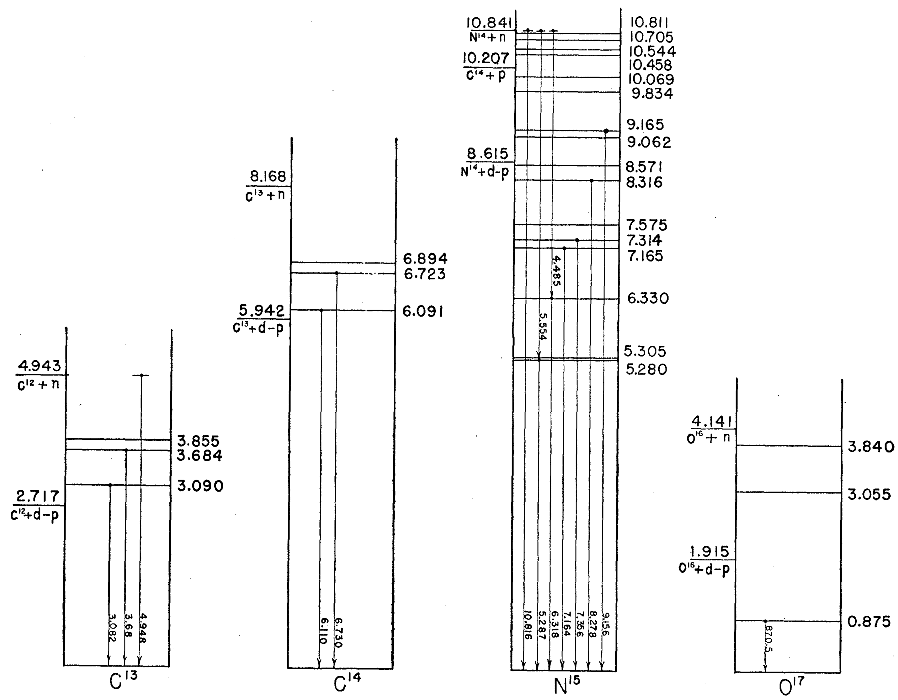

FIG. 2. Energy-level diagrams for C^{13}, C^{14}, N^{15}, and O^{17}.

[9] G. A. Bartholomew and B. B. Kinsey, Can. J. Phys. **31**, 49 (1953).
[10] R. G. Thomas and T. Lauritsen, Phys. Rev. **78**, 884 (1950).
[11] Mackin, Mims, and Mills, Phys. Rev. **93**, 950 (1954).
[12] Bent, Bonner, and Sippel, Phys. Rev. **95**, 649 (1954).

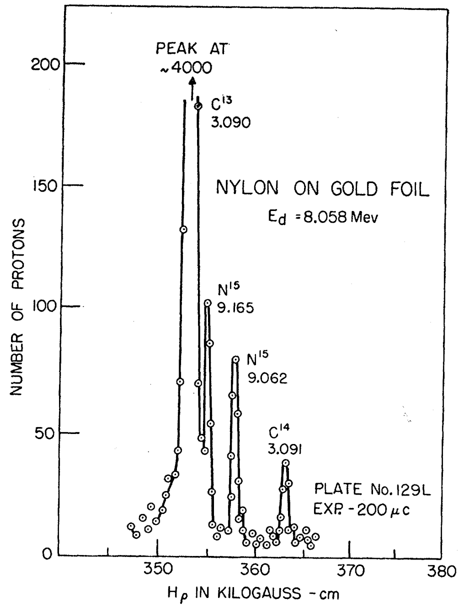

FIG. 3. Proton spectrum from 8-Mev deuteron bombardment of a nylon target showing the N^{15} 9.165 group resolved from the C^{13} 3.090 group.

5 and 6 Mev. The region between 2 and 8.1 Mev represented in Fig. 1 shows only the three groups mentioned above. Within this region, a group with intensity less than 20 percent of the intensity of the group corresponding to the 6.091-Mev level would not have been observed. A group corresponding to the reported[4] pair-emitting state at 4.1 Mev in C^{14} should occur in Fig. 1 at about 400 kilogauss-centimeters. Because of the background from gold and the intense C^{13} and O^{17} groups, a weak group here from C^{14} could easily have been obscured.

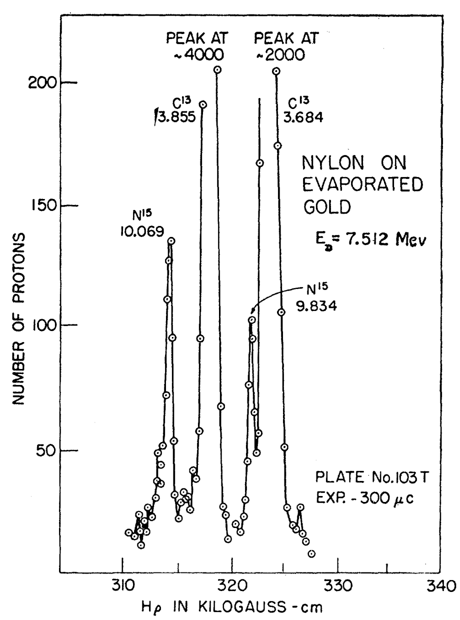

FIG. 4. Proton spectrum of a 7.5-Mev deuteron bombardment of a nylon target showing the N^{15} 9.834 group.

The $N^{14}(d,p)N^{15}$ Reaction

The present study of the reaction $N^{14}(d,p)N^{15}$ combined with the earlier investigation at lower bombarding energy covers the complete region of excitation from the ground state up to the neutron binding energy in N^{15}. Of a total of seventeen proton groups attributed to this reaction, fourteen are clearly shown in the lower part of Fig. 1. The highest-energy group corresponding to the ground-state transition was not analyzed in the present work since it fell outside the range of the spectrograph even at the lowest (5.0 Mev) bombarding energy used. The single peak at $H\rho=327$ kilogauss-centimeters is a superposition of a N^{15} 9.165 group with the strong C^{13} 3.090 group at the 7.0-Mev bombarding energy. That this is so can be seen from Fig. 3, where this same region of the spectrum is reproduced for a bombarding energy of 8.0 Mev. The N^{15} 9.165 group here appears completely resolved from the C^{13} 3.090 peak. A group reported by Gibson and Thomas[13] at 9.22 Mev from photographic-plate range measurements is probably due to the pair of levels at 9.062 and 9.165 Mev observed here.

The remaining group not prominent in Fig. 1 should appear at $H\rho$ of 306 kilogauss-centimeters. The spectrum between 295 and 320 kilogauss-centimeters was obtained from two exposures at different field settings which were not sufficiently overlapped. The N^{15} 9.834 group was thus mostly obscured in the background of the prolific C^{13} groups, close to an edge of both photographic plates. Figure 4 shows a more adequate exposure of this region of the spectrum obtained at a bombarding energy of 7.5 Mev.

The group corresponding to the level at 7.575 Mev was not observed in the previous MIT work because of the high background of protons from the O^{17} 0.875 group. With this exception, the two investigations are in excellent agreement where they overlap.

In Table I are summarized the Q values for $N^{14}(d,p)N^{15}$ and the excitation energies in N^{15} determined from the present work, together with the previous MIT measurements. The ground-state Q value of 8.615 Mev was used in calculating the excitation energies in both cases. Also tabulated are excitation energies derived from the gamma-ray energies observed from the $N^{14}(n,\gamma)N^{15}$ reaction by Kinsey *et al.*[14]

A comparison of the three sets of data where the observations overlap shows excellent agreement, except for the two gamma rays assigned to the levels at 7.314 and 8.316 Mev. The deviations from the present (d,p) results amount to $+42$ and -38 kev, respectively,

[13] W. M. Gibson and E. E. Thomas, Proc. Roy. Soc. (London) **A210**, 543 (1952).

[14] Kinsey, Bartholomew, and Walker, Can. J. Phys. **29**, 1 (1951).

whereas the average difference for the remaining four level positions is 5 kev. The reason for this discrepancy has not been found.

A level diagram for N^{15}, incorporating all the data from Table I, is included in Fig. 2. The set of vertical arrows represent the possible gamma-ray transitions that can be correlated with the nitrogen capture radiations reported by Kinsey *et al.*[14] The values of their gamma-ray energies are indicated along the vertical line. The absence of a gamma ray that can be associated with the 7.575 level may indicate the operation of selection rules forbidding such a transition. However, because of the presence of a strong background radiation of 7.7 Mev from aluminum, it appears possible that a weak 7.6-Mev gamma ray from nitrogen might not have been observed.

TABLE I. Q values for the $N^{14}(d,p)N^{15}$ reaction and excited states in N^{15}.

Q values (Mev)		Excitation energies in N^{15} (Mev)		
Present work $E_d=5$ to 8 Mev ± 0.010	Previous MIT work[a] $E_d=1.5$ Mev $\leq \pm 0.010$	Present work	Previous MIT work[a] ± 0.006	Kinsey *et al.*[b] $N^{14}(n,\gamma)N^{15}$ $\sim\pm 0.015$
	8.615		0	
3.335	3.339	5.280	5.276	5.275
[c]	3.310	···	5.305	···
2.285	2.287	6.330	6.328	6.325
1.450	1.451	7.165	7.164	7.164
1.301	1.306	7.314	7.309	7.356
1.040	···	7.575	···	···
0.299	0.300	8.316	8.315	8.278
0.044	···	8.571	···	···
−0.447	···	9.062	···	···
−0.550	···	9.165	···	9.156
−1.219	···	9.834	···	···
−1.454	···	10.069	···	···
−1.843	···	10.458	···	···
−1.929	···	10.544	···	···
−2.090	···	10.705	···	···
−2.196	···	10.811	···	···

[a] See reference 3.
[b] See reference 14.
[c] Not sufficiently resolved.

From a recent study of gamma-ray resonances from proton bombardment of C^{14}, Bartholomew *et al.*[15] have observed resonances at proton energies of 0.36, 0.53, and 0.64 Mev, corresponding to levels in N^{15} at 10.567, 10.737, and 10.847 Mev, respectively, in excellent agreement with our measurements.

Because of the close spacings of a number of the new groups, two or more appeared on the same photographic plate. This made possible a more accurate determination of their separation. In Table II are listed the separations of those adjacent groups that were observed on the same plate. It should be noted that the data on separations were not used in computing the excitation energies.

There has been considerable speculation regarding the closely spaced pair of levels at 5.3 Mev.[16] A study, now under way, of the angular distributions of the proton groups from this reaction may help in determining the nature of these levels.

TABLE II. Spacings for some adjacent groups from the $N^{14}(d,p)N^{15}$ reaction.

Group interval (Mev) From	To	Spacing in kev
7.165	7.314	149±4
7.314	7.575	263±5
8.316	8.571	258±4
9.062	9.165	103±4
9.834	10.069	239±6
10.458	10.544	85±3
10.544	10.705	160±4
10.705	10.811	105±3

The $O^{16}(d,p)O^{17}$ Reaction

The four groups from the $O^{16}(d,p)O^{17}$ reaction have all been observed previously. In earlier measurements in this Laboratory at lower bombarding energies, only the ground-state group and the group corresponding to the 0.875 level were observed. The present work extends the survey to include the groups corresponding to the levels in O^{17} at 3.055 and 3.840 Mev. Burrows, Powell, and Rotblat[17] have previously reported these groups in addition to groups from the $F^{19}(d,\alpha)O^{17}$ reaction leading to the same levels in O^{17}. Watson and Buechner[18] have also investigated the $F^{19}(d,\alpha)O^{17}$ reaction in this region of excitation.

A summary of these results appears in Table III. The slight discrepancies in the excitation energies of O^{17} between the present results from the $O^{16}(d,p)O^{17}$ reaction and those of Watson and Buechner from the $F^{19}(d,\alpha)O^{17}$ reaction are within the experimental errors. However, the fact that the level positions from the latter reaction are consistently higher than the new values is presumably due to the uncertainty mentioned in the earlier work regarding target contamination. An

TABLE III. Q values for the $O^{16}(d,p)O^{17}$ reaction and excitation energies in O^{17}.

Q values (Mev), $O^{16}(d,p)O^{17}$			Excitation energies (Mev) in O^{17}			
Present work $E_d=5$ to 8.5 Mev ± 0.010	Previous MIT results[a] $E_d=1.5$ Mev ± 0.005	Burrows *et al.*[b] ± 0.02	Present work $E_d=5$ to 8 Mev ± 0.012	Previous MIT results[a] $O^{16}(d,p)O^{17}$	Previous MIT results[a] $F^{19}(d,\alpha)O^{17}$	Burrows *et al.*[b] $O^{16}(d,p)O^{17}$ $F^{19}(d,\alpha)O^{17}$
1.915	1.917	1.93	0	0	0	0
1.040	1.037	1.06	0.875	0.880±0.005	0.883±0.012	0.87±0.02
−1.140		−1.14	3.055		3.069±0.012	3.06±0.02
−1.925		−1.94	3.840		3.856±0.012	3.85±0.02

[a] See references 1 and 18.
[b] See reference 17.

[15] Bartholomew, Brown, Gove, Litherland, and Paul, Phys. Rev. **95**, 649 (1954).

[16] D. R. Inglis, Revs. Modern Phys. **25**, 390 (1953).

[17] Burrows, Powell, and Rotblat, Proc. Roy. Soc. (London) **A209**, 478 (1951).

[18] H. A. Watson and W. W. Buechner, Phys. Rev. **88**, 1324 (1952).

energy-level diagram for O^{17} is included in Fig. 2, which also shows the 870.5±2.0 kev gamma ray reported by Thomas and Lauritsen.[10]

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Proton-Proton Scattering at 5.77 Mev*

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Absolute differential scattering cross sections for proton-proton scattering at laboratory energies of 5.77 and 5.86 Mev (±1 percent) have been obtained with an accuracy of about one percent at many angles (23° to 110° c.m.) by two independent experiments, one employing nuclear emulsion plates as detectors and the other employing proportional counters. Reduced to the same energy, the average indicated S-wave nuclear phase shift is in excellent agreement with other data for this energy region. However, at small scattering angles, important for determining a P-wave phase shift, the measured cross sections differed originally by 3 to 5 percent, the nuclear emulsions method indicating a P-wave shift of -0.08 ± 0.05 degree, and the original counter data indicating -0.34 ± 0.05 degree. After the beam collimation was improved and the energy spectrum of the incident proton beam was examined, check runs with the counters at six scattering angles failed to indicate the large P-wave effect, giving -0.08 ± 0.07 degree, in agreement with the emulsion data. It therefore appears likely that the P-wave shift at this energy is small (less than 0.1 degree) and negative, in agreement with other determinations in this energy region.

I. INTRODUCTION

Results of the proton-proton scattering experiments carried out over a period of several years at the University of Illinois Cyclotron Laboratory will be reported here. While some of the data have already been published in preliminary form,[1,2] this report gives a complete analysis of the experiments, together with some additional information.

Two separate methods were used to measure the differential scattering cross sections. The two experiments were almost completely independent, only the device for measuring the charge being common to both. One experiment employed the scattering chamber constructed by Rodgers, Meagher, and Leiter[3–5] in which the scattered protons were recorded in nuclear emulsions. The second method used a scattering chamber in which scattered protons were detected by proportional counters used in coincidence to eliminate the effect from background radiation produced by the cyclotron.

A number of studies of proton-proton scattering in the low-energy region (below about 10 Mev) have been made. Reference will be made here only to some fairly recent theoretical analyses which contain references to early theoretical and experimental work.[6–11] Reference will also be made to some very recent experimental papers,[12–17] most of which also contain bibliographies.

II. NUCLEAR EMULSION EXPERIMENT[18]

The scattering chamber, used previously by Rodgers,[3] Leiter,[4] Meagher,[5] and concurrently by Kreger,[19] is constructed so that particles scattered over a wide range of angles are recorded simultaneously on six

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