Proton Groups from the Deuteron Bombardment of Aluminum, Sodium, and Manganese*

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Thin targets of sodium, aluminum, and manganese were bombarded with 3.0-Mev deuterons from the large electrostatic generator at the Department of Terrestrial Magnetism, and the protons were observed at 90 degrees to the beam with an argon filled proportional counter. The counter was biased to count protons at the end of their range and the ranges of the groups were measured in air and aluminum. Proton groups due to oxygen and carbon were found with all targets.

1. INTRODUCTION

MEASUREMENT of the energy of the proton groups emitted in the (d,p) reactions yields a method for determining the energy levels in the residual nucleus. A number of elements have been investigated with this type of reaction and extensive data are available on nuclear energy levels and energy level spacings.[1]

The proton groups from the $Na^{23}(d,p)Na^{24}$ were investigated by Lawrence[2] at a bombarding energy of 2.15 Mev and by Murrell and Smith[3] at a bombarding energy of 0.85 Mev. Lawrence found two groups of protons which gave Q-values of 4.92 and 1.72 Mev but the low energy groups were not investigated, Murrell and Smith found seven groups of protons, but two of these they attributed to $O^{16}(d,p)O^{17}$ and one to $H^2(d,p)H^3$, the remaining groups gave Q-values of 1.38, 3.50, 4.58 and 4.76 Mev respectively. The proton groups from the $Al^{27}(d,p)Al^{28}$ reaction were investigated by McMillan and Lawrence[4] at a bombarding energy of 2.2 Mev, by Schultz, Davidson, and Ott[5] at a bombarding energy of 3.2 Mev, rather thoroughly by Pollard, Sailor, and Wyly[6] with various bombarding energies and a maximum of 3.8 Mev, and by Allan and Clavier[7] at a bombarding energy of 0.9 Mev. McMillan and Lawrence found evidence of five distinct groups, while Schultz, Davidson, and Ott using a cloud chamber to detect the protons, found groups whose ranges were in rough agreement with those of McMillan and Lawrence but whose intensities differed. Allen and Clavier found three groups at the lower bombarding energy, while Pollard *et al.* found 14 groups of protons and 4 groups of alphas. The protons from $Mn^{55}(d,p)Mn^{56}$ were investigated by Martin[8] at a bombarding energy of 3.6 Mev; he resolved five groups of protons which he attributed to the $Mn^{55}(d,p)Mn^{56}$ reaction.

Two other reactions that have been investigated are the $O^{16}(d,p)O^{17}$ reaction,[9] and the $C^{12}(d,p)C^{13}$ reaction.[10] These two reactions are particularly important because the elements appear as contaminants on all targets unless special precautions are taken to remove them. Oxygen forms a thin oxide layer on the target, and since the cross section is large, the proton groups from this reaction are generally present. Thin layers of carbon are deposited on the targets from the diffusion pumps. The yield curves for these reactions have been determined[9,10] and by determining the yield-curve of a proton group which comes at the proper range for one of these contaminants the amount of the contaminant can be estimated.

The well-defined energy of the bombarding particles from the source, and the fact that the energy available was higher than with similar previous experiments, combined with a more detailed knowledge of the yield curves of carbon and oxygen, made it seem worth while to reinvestigate the proton groups from the (d,p) reactions of sodium, aluminum, and manganese.

2. EXPERIMENTAL APPARATUS

The pressurized electrostatic generator at the Department of Terrestrial Magnetism was used as the source of high energy deuterons. The voltage was measured with a generating voltmeter using the $Be(p,n)$ threshold (2.035 Mev), the $Li^7(p,n)$ threshold (1.87 Mev) and the fluorine (p,γ) 873-kev resonance as calibrating points. The current, which was generally of the order of one microampere, was measured with a current integrator designed by M. Sands.

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† Part of this work done while an AEC Predoctoral Fellow. Now at Bartol Research Foundation, Swarthmore, Pennsylvania.
[1] E. C. Pollard, Nucleonics 2, 4 (1948).
[2] E. O. Lawrence, Phys. Rev. 47, 17 (1935).
[3] E. B. Murrell and C. L. Smith, Proc. Roy. Soc. A173, 410 (1939).
[4] E. M. McMillan and E. O. Lawrence, Phys. Rev. 47, 343 (1935).
[5] Shultz, Davidson, and Ott, Phys. Rev. 58, 1043 (1940).
[6] Pollard, Sailor, and Wyly, Phys. Rev. 75, 727 (1949).
[7] H. R. Allan and C. A. Clavier, Nature 158, 832 (1946).
[8] A. B. Martin, Phys. Rev. 72, 378 (1947).
[9] N. P. Heydenburg and D. R. Inglis, Phys. Rev. 73, 230 (1948).
[10] N. P. Heydenburg *et al.*, Phys. Rev. 75, 1147 (1949).

In the early portion of the work the protons were detected with a 3-mm deep ionization chamber, but a proportional counter was found to be more satisfactory because of the shorter resolving time, and the gas amplification; and all of the data except the manganese number *vs.* range curve were taken with a proportional counter. These were the same counters that were used in this laboratory in the previous experiments with oxygen,[9] carbon,[10] and lithium.[11] The pulses from the counter were amplified by a preamplifier and a linear amplifier and counted with a scale of 64 counter and a mechanical register.

The counters were mounted at 90 degrees to the bombarding beam on a vernier screw so that the range in air could be changed accurately. Gross changes in the range were made using aluminum foils of 2.54 and 5.2 cm air equivalent, and the fine changes were made with the screw. The discriminator for the scaler was set to measure only those particles near the end of their ranges and the number of particles was corrected for the decrease in intensity with increasing range.

Thin targets were deposited on a backing foil and then mounted so that the beam struck them at an angle of 45 degrees, and the protons were observed at 90 degrees to the beam. The target chamber for aluminum and manganese was a brass tube with a side arm with an aluminum window mounted over the end. The targets were mounted and slipped in the end of the tube so that they were opposite the side arm. The sodium target chamber was similar but had a sodium boiler incorporated so that targets could be prepared in the vacuum system. The diameter of the beam was $\frac{1}{4}$ inch and the window on the front of the counter was 3×5 mm.

The sodium target was prepared by evaporating the pure metal from the boiler onto a $\frac{1}{32}$-in. silver foil mounted on a $\frac{1}{16}$-in. thick copper plate which held the silver in place and served as a heat conductor. Gold foil was tried as a target backing but sodium and gold form an amalgam which makes the target thick. The thickness of the sodium target was judged entirely by eye, and no measurements of thickness were made. The sodium was evaporated on until there was a visible even layer.

The aluminum and manganese targets were both prepared by evaporating the pure metal onto thin gold foils in an auxiliary vacuum system. Small pieces of aluminum and magnanese were melted onto tungsten filaments and then evaporated onto the foils. The thickness of the manganese target was measured by measuring the change in equivalent cm of air of the gold foil before and after the manganese was evaporated on. The change in range due to target thickness was less than 1 mm of air.

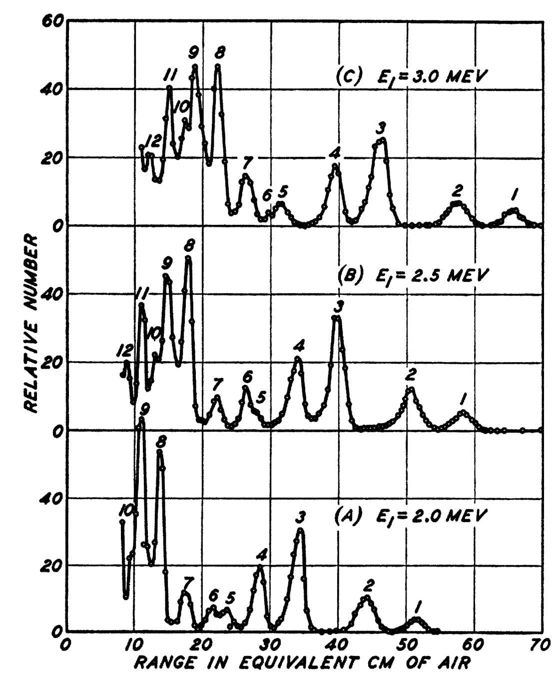

FIG. 1. Relative number of protons *vs.* equivalent range in air for protons from $Na^{23}(d,p)Na^{24}$; E_1 is bombarding energy.

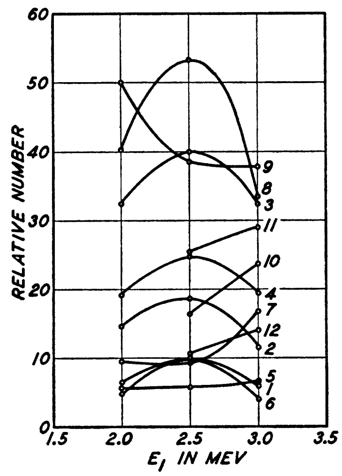

FIG. 2. Yield curve for proton groups taken from Fig. 1, *A*, *B*, *C*, normalized to group 3.

3. RESULTS

Nine groups of protons were found when the thin sodium target was bombarded with 2.0-Mev deuterons and 12 groups when the bombarding energy was 2.5 and 3.0 Mev. These groups are plotted in Fig. 1 in which the relative number of protons per integrator count is plotted *vs.* the equivalent range in air. The points on the higher intensity peaks represent several thousand protons. Two of the groups of protons (10, Fig. 1A) (7, 10, Fig. 1B, C) have the same ranges as the protons from the $O^{16}(d,p)O^{17}$ reaction, but they come in a region of high density of proton groups from the sodium and the intensities do not follow the observed yield curve for oxygen so the Q-values were computed as if the groups were from sodium. The range of group 5 does

[11] N. P. Heydenburg *et al.*, Phys. Rev. 74, 405 (1948).

not vary with bombarding energy in the same fashion as does group 6 and must be from a different nucleus, and since it gives the correct Q-value for the $C^{12}(d,p)C^{13}$ reaction at all three bombarding energies we have attributed it to carbon, although the yield curve of this group does not follow that observed for carbon.

The number *vs.* range curves were all taken using the same sodium target, and after all the data were taken a yield curve was taken for group 3 to normalize the yields of the different groups at the different energies. The intensity of a group is approximately proportional to the product of the height of the group and the width at half-maximum. The intensities of the individual groups were determined in this way and Fig. 2 gives the excitation curve for the individual groups. The intensities of the complex groups were taken as the product of the group height and the width at half-maximum as determined from Bethe's straggling curves.[12]

The yield curve for group 5 (Fig. 2) does not follow the observed yield curve for carbon at higher energies the observed yields being

$$Y_{2.0}/Y_{2.5}=65/70, \quad Y_{2.0}/Y_{3.0}=65/30.$$

This discrepancy is probably due to the background of sodium protons. The yield curve for the long range oxygen group ($O_{L.R.}$) compares with group 7 as follows:

$$Y_{2.0}/Y_{2.5}=9.5/9.3, \quad O_{L.R.} \text{ observed } 9/16,$$
$$Y_{2.0}/Y_{3.0}=9.5/16.6, \quad O_{L.R.} \text{ observed } 9/32.$$

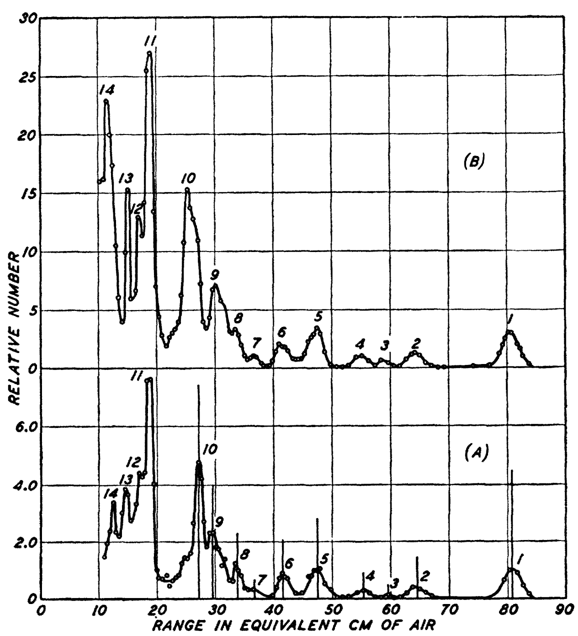

FIG. 3. Relative number of protons *vs.* equivalent range in air for protons from $Al^{27}(d,p)Al^{28}$. Curve *A* is thin target; Curve *B* is slightly thicker. Bombarding energy is 3.0 Mev.

[12] M. S. Livingston and H. A. Bethe, Rev. Mod. Phys. **9**, 245 (1937).

TABLE I. Q-values for $Na^{23}(d,p)Na^{24}$.

Present experiment Bombarding energy 2.0	2.5	3.0	Murrel and Smith Bombarding energy 0.85	Lawrence Bombarding energy 2.15
4.81	4.82	4.69	4.76	4.92
4.25	4.28	4.16	4.38	
3.46	3.43	3.47	3.50	
2.92	2.95	2.94		
2.21	2.25	2.19		
1.29	1.34	1.36	1.38	1.72
0.93	0.95	1.01		
	0.74	0.83		
	0.47	0.53		
	0.14	0.11		

The yield curve for group 9 departs from the general shape of the long range groups, and all of the short range groups increase in intensity with bombarding energy. If group 10 were entirely due to oxygen the intensity would decrease as the energy was increased from 2.0 to 3.0 Mev, but the intensity increases by a factor of 1.5 so that the group must be due mostly to sodium. The total yield curve as measured by the radioactivity of the Na^{24} for the $Na^{23}(d,p)Na^{24}$ increases up to a bombarding energy of 5.5 Mev.[1] The Q-values for this reaction as computed from the number *vs.* range curves are given in Table I.

A thin target of aluminum was bombarded with 3-Mev deuterons and 14 groups of protons were observed (Fig. 3A). In general the number *vs.* range curve for this reaction is similar to that determined by Pollard *et al.* but there are discrepancies in the Q-values computed from these ranges. A slightly thicker target of aluminum was bombarded at 3.0 Mev, the thickness was not actually measured but the number of protons increased by a factor of four. The number *vs.* range curve for this target (Fig. 3B) was essentially the same as for the thin target, but the range of the peak of group ten had shifted one cm. Two of the fourteen groups of protons have the same ranges as the protons from $O^{16}(d,p)O^{17}$ (10, 11, Fig. 3) and one has the same range as the protons from $C^{12}(d,p)C^{13}$ (8, Fig. 3). The oxide layer is likely to be a constant independent of the thickness of target, but group 10 which comes at approximately the right range for the oxygen shifted about one cm in range when the target was made thicker, and must be partly due to oxygen and aluminum at slightly different ranges. The observed ratio of the intensities of the short range oxygen group to the long range group is 1.25 at 3.0 Mev and the ratio as determined from Fig. 3B is 26/31; the observed ratio for these groups (9, 10) at 2.2 Mev is 7 and the ratio is 12/20 when the bombarding energy is 2.2 Mev so that the groups must be due to aluminum. The vertical lines drawn through the peaks of the thin aluminum curve are proportional to the intensity and are equal to the product of the group height and the width of the group at half-maximum. This illustrates the role of straggling in determining the intensity, for although the group

TABLE II. Q-values for $Al^{27}(d,p)Al^{28}$.

Present experiment thin	Present experiment ½ thin	Pollard *et al.*	Allan and Clavier
5.71	5.72	5.45	5.49
4.71	4.71		
4.32	4.39	4.42	4.49
4.07	4.07	3.88	
3.49	3.49	3.29	3.34
3.04	3.06		
2.72	2.66	2.84	
2.39	2.40	2.48	
2.11	2.05	2.04	
1.59	1.80	1.55	
0.95	0.93	0.98	
0.70	0.70	0.73	
0.47	0.45	0.57	
−0.05	0.13	0.29	
		0.01	
		−0.31	

heights of the long range groups are low, the intensities are high. The Q-values as computed from the number *vs.* range curves are given in Table II.

A thin manganese target was bombarded with 3.0 (Fig. 4) and 2.2-Mev deuterons and ten proton groups were observed at 3.0 Mev. Groups 6 and 7 have the same range as the oxygen groups and group 5 has the same range as the carbon group. In the observed yield curve the ratio of the intensities of the short range oxygen group to the long range oxygen group at 3.0 Mev is 1.25 and in this curve it is 1, while the ratio at 2.2 Mev is 7 and in this case it is 10. The discrepancies in these ratios are probably due to the background of protons from manganese, and the groups are probably mostly due to oxygen. Assuming that group 7 follows the yield curve for the short range oxygen group, group 5 increases by a factor of 2.5 as the bombarding energy

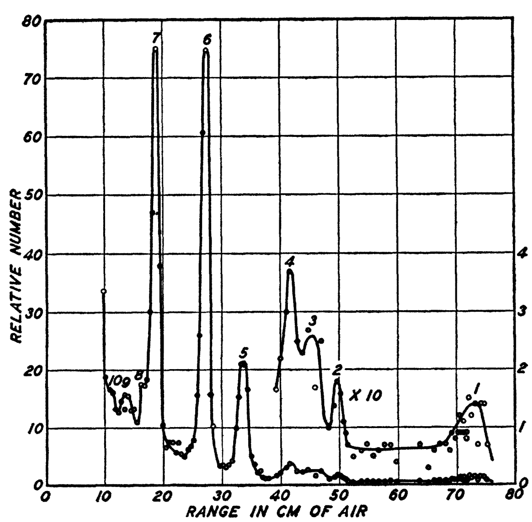

Fig. 4. Relative number of protons *vs.* equivalent range in air for protons from $Mn^{55}(d,p)Mn^{56}$; bombarding energy 3.0 Mev. The intensity is expanded by a factor of ten for the long range groups.

TABLE III. Q-values for $Mn^{55}(d,p)Mn^{56}$.

Present experiment	Martin
5.01	4.76
3.47	3.69
3.13	
2.85	2.99
0.48	2.28
0.13	1.15
−0.19	

TABLE IV. Range of protons scattered from silver foil.

Bombarding energy Mev	Scattered proton energy Mev	Range (NTP) cm	Range (Herb) cm	Range (Bethe) cm
1.1	1.066	2.46	2.48	2.54
1.2	1.163	2.83	2.85	2.92
1.5	1.45	4.12	4.10	4.15
1.6	1.55	4.58	4.57	4.63
1.8	1.745	5.63	5.53	5.63
2.0	1.94	6.72	6.62	6.74
2.25	2.18	8.11		8.25
2.5	2.42	9.59		9.75
3.1	3.005	14.10		14.15

is decreased from 3.0 to 2.2 Mev, while the observed yield for carbon increases by a factor of 3, and the group must be due to carbon. For the high intensity groups there were several hundred protons counted per point; while for the low intensity peaks there were of the order of 50 protons per point. There are 7 observed groups of protons which are attributed to manganese and the Q-values are listed in Table III.

4. RANGE AND INTENSITY MEASUREMENTS

The range to the counter for each measurement was made up of the aluminum window on the target chamber, several centimeters of air, the aluminum absorbing foils, the aluminum counter window, and the argon in the counter. The stopping powers of the individual foils and windows were measured by measuring the change in range of protons of known energy scattered at 132.5 degrees from a silver leaf. The range to the center of the counter was then reduced to equivalent cm of air and plotted on the number *vs.* range curve. Since the actual range in air never exceeded 2.5 cm there was no correction made for temperature and pressure variation. The details of the conversion to equivalent cm of air from the aluminum foils have been discussed in a previous paper by Heydenburg, Inglis, Whitehead and Hafner.[10]

The range of a group of protons was computed by adding 0.2 cm to the range to the peak of a group. The counter was biased such that the maximum pulse height occurred when the counter straddled the Bragg peak; thus the range to the peaks in the number *vs.* range curve represents the mean range to the peak of the Bragg curve. The range of the group is this range plus

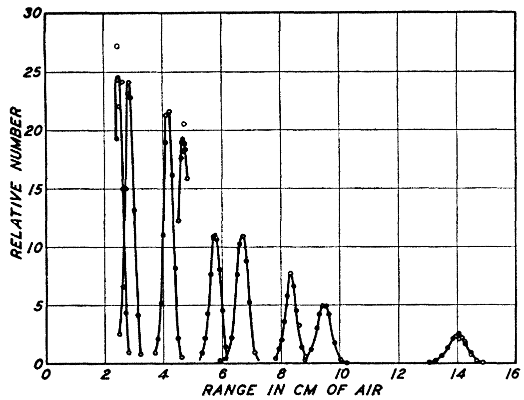

FIG. 5. Relative number of protons *vs.* range in air of protons scattered at 132.5 degrees from a silver leaf at bombarding energies of 1.1, 1.2, 1.5, 1.6, 1.8, 2.0, 2.25, 2.5, and 3.1 Mev.

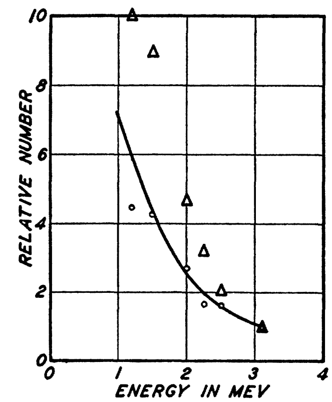

FIG. 6. Area under peaks of Fig. 5 *vs.* bombarding energy and peak heights of Fig. 5 *vs.* bombarding energy. Peak heights and areas are normalized for long range group. Solid line is $AE^{-2}\times 10$ with A an arbitrary constant.

0.2 cm as deduced from the Bragg curve for protons as given by Holloway and Moore.[13]

Figure 5 is the number *vs.* range curve for the protons scattered from a silver leaf at 132.5 degrees. In these curves corrections were made for temperature variations since most of the range is in air. The ranges deduced from the curve for the given energy are given in Table IV.

The intensity of the scattered protons should vary as AE^{-2} as the bombarding energy is increased, where A is an arbitrary constant. The ratio of the peak height to the 3.1-Mev peak and the ratio of the area under the peak to the area under the 3.1 new peak are plotted *vs.* energy in Fig. 6. A curve of the form AE^{-2} is normalized to this peak and from this can be seen that intensity is proportional to the area under the curve rather than to the peak height. This is to be expected since the counter measures number per unit length because of its finite depth, and the intensity of the product of the distance and this number.

One of us (W.D.W.) would like to thank, Dr. M. A. Tuve for making the facilities at the Department of Terrestrial Magnetism available for the work.

[13] M. G. Holloway, and B. L. Moore, Phys. Rev. **58**, 847 (1940).