Protons from Carbon and Aluminum Bombarded by Deuterons

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The design of a cloud chamber and the technique of its use are described. With it a study of the protons from deuteron bombardment of carbon and aluminum has been made. The group corresponding to the ground state of C^{13} appears to be single. The protons from Al^{27} show a general distribution in agreement with the work of McMillan and Lawrence; but analysis into groups is difficult as there appear to be many such, with small spacing. Curves are shown from which any group structure can be inferred. The homogeneity of the deuteron beam was tested by scattering the deuterons from a thin gold foil: It is homogeneous to within 0.15 Mev.

INTRODUCTION

PROPORTIONAL counters and ionization chambers have been used almost exclusively in studies of the group structure of charged particles emitted in nuclear transmutations. These methods have disadvantages, in particular when a cyclotron is employed. Weak groups are hard to detect in the presence of a high neutron background. The necessity of a high counting level for discriminating against β- and γ-radiations makes the determination of absolute yields a difficult problem. This feature may lead to incorrect values of the relative intensities of groups of different width and symmetry.

Theoretical considerations indicate that the density of nuclear energy levels varies rapidly with excitation energy and number of particles of which the nucleus is composed. Resolution is important in investigations of groups from heavier nuclei where counting methods may show definite groups with larger spacings than predicted by theory.

An attempt has been made to overcome the above difficulties in studies of *dp* reactions by allowing the emitted protons to register in an expansion chamber. Bower and Burcham[1] have applied this method in experiments on proton groups from fluorine bombarded by deuterons, and have pointed out that it affords a means of achieving high resolving power without serious limitation of solid angle. A desirable feature of the method is that the determination of relative amplitudes of groups does not involve an integration of the incident beam intensity.

This paper gives the results of a cloud-chamber investigation of the protons from carbon and aluminum bombarded by 3.2-Mev deuterons produced in the Yale cyclotron. General details of construction and performance of this cyclotron have already been mentioned.[2]

APPARATUS AND EXPERIMENTAL PROCEDURE

The cloud chamber, 17 cm in diameter, is of the moving diaphragm type. Best results were obtained with a semirigid diaphragm made by cementing a circular aluminum plate $\frac{3}{32}''$ thick to the rubber diaphragm itself. Argon and ethyl alcohol vapor were used with a relative stopping power of 1.18 as determined both by calculation and calibration with Th C′ alpha-particles. This mixture has the advantage that much fewer recoils and disintegrations produced by neutrons are noted than would be the case with air.

Single photographs were taken with an automatic camera. Since the tracks were highly collimated in a horizontal plane, stereoscopic photographs were unnecessary. Two high speed argon-filled discharge tubes of the design by Edgerton[3] served to give ample illumination. With Agfa Ultraspeed Panchromatic film enough light was present to permit an aperture of $f:9$, thus providing good depth of focus. This lighting scheme proved to be quite successful and convenient. A photograph of tracks is shown in Fig. 1.

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[1] J. C. Bower and W. E. Burcham, Proc. Roy. Soc. **173**, 379 (1939).
[2] E. Pollard, W. L. Davidson, Jr. and H. L. Schultz, Phys. Rev. **57**, 1117 (1940).
[3] H. E. Edgerton, K. J. Germeshausen and H. E. Grier, Phot. J. **76**, 198 (1936).

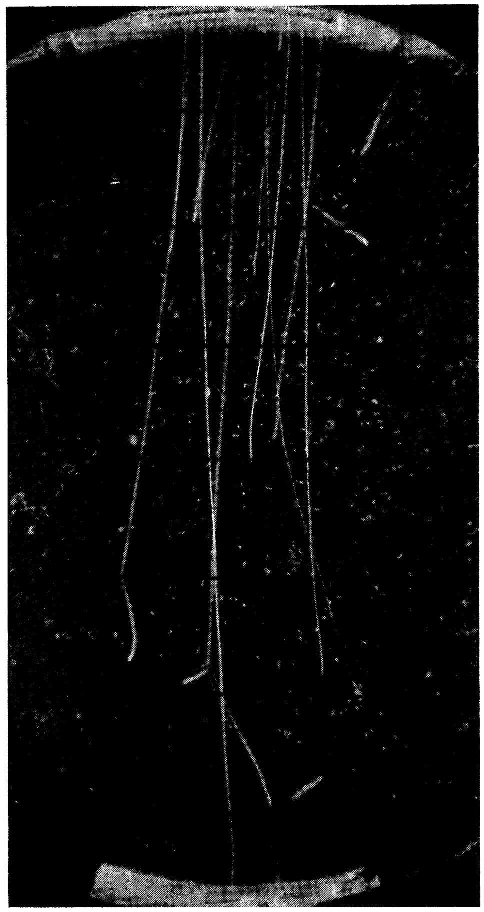

FIG. 1. Protons from aluminum bombarded by deuterons.

Solid targets were mounted directly in the target chamber of the cyclotron. For targets in gaseous form a special cell was built into the target box and isolated from the acceleration chamber by a 2.7-cm air equivalent foil. Protons from the target passed down an evacuated tube and entered the cloud chamber 45 cm from the target proper. All observations were made at a mean angle of 87° with respect to the incident beam, with an angular spread of less than 4° in the horizontal plane and a spread not exceeding $\frac{1}{2}$° in the vertical. Particles suffering small angle scattering with the walls of the evacuated tube were prevented from entering the slot in the cloud chamber by a series of diaphragms. Fog produced by background radiations from the cyclotron was not at all troublesome. In order to make each track clearly distinguishable, an effort was made to keep the number per expansion less than fifteen.

Groups were caused to end successively in the expansion chamber by interposing aluminum foils between the chamber and target. Each foil represented one-half of the total absorption experienced by a particle traversing the diameter of the chamber. This gave rise to overlapping of data with consecutive foils, and thus data taken with different foils could be properly joined up so as to permit the determination of relative intensities of groups.

Homogeneity of the Cyclotron Beam

A knowledge of the homogeneity in energy of the incident beam used for bombardment is essential in experiments of the kind being described. Several methods first used in the estimation of spread in energy of the deuteron beam were: (1) visual observation of the beam in air; (2) measurement of the beam current to a collector as a function of absorption introduced in the path of the beam. These preliminary measurements indicated a spread of 0.5 Mev. However, these methods are open to considerable error, and our final estimation is based on the following experiment.

The number-range distribution of deuterons scattered from the beam by a thin gold foil (1 mm air equivalent) was obtained by allowing the scattered particles to enter the cloud chamber. In this case a relative stopping power of 0.71 was used. The angular divergence of the scattered beam was made less than 2°. Figure 2 shows the results. The observed distribution has a width at half-maximum of 0.19 Mev. It is difficult to estimate how much of this width is caused by range straggling introduced by the foils and gas in the chamber. From the distribution curve the difference between extrapolated and mean range is 8 percent of the mean range. Theoretically, if the incident beam were homogeneous, this quantity would be expected to be about 2 percent. If one allows for non-uniformity in the thickness of the foils, 5 percent may be taken as a reasonable figure for the beam itself.

The lower energy peak of small intensity may perhaps be attributed to inelastic scattering. However, if that is the case it is difficult to understand why this peak should be well defined in view of the close spacing of nuclear levels in gold. Most likely, it is to be associated with two more or less effectively defined ion centers from which ions are withdrawn for acceleration. This condition will of course depend strongly upon the magnetic field corrections used to get a beam, available dee voltage, and clearance between deflector plate and dee. It should be noted that our cyclotron employs the simple filament ion source, and hence ions can be withdrawn from more than one point.

These results indicate a better degree of homogeneity in energy than found with other cyclotrons.[4] This is no doubt because in our case small radiofrequency power input (2 kw) has been used. This, together with a small clearance between deflector plate and dee, imposes the requirement that the beam energy be accurately defined in order that it may be withdrawn into the target chamber.

Protons from C^{12}

The assumption of Russell-Saunders coupling between spins and orbital momenta in the nucleus C^{13} suggests a doublet of which the lower level is the ground state.[5] The separation between the components of the doublet might be expected to be of the order of a few tenths of a Mev with an intensity ratio of 2 : 1, i.e., ratio of statistical weights of the two levels. Whether the spin of the ground state is $\frac{1}{2}$ or $\frac{3}{2}$ depends upon the particular nuclear model chosen. The assumption of a doublet character is in accord with observations of Richardson[6] that a 280-kev γ-ray appears to be emitted in the transition $N^{13} \rightarrow C^{13} + e^{+}$; also, additional support of this assumption is found in the work of Cockcroft and Lewis[7] who found that the group of protons from carbon bombarded by deuterons is wider than the deuteron-deuteron group. The opposite should be expected if the carbon group is associated with a single level in C^{13}.

An attempt to observe a definite asymmetry in the group of protons arising in the reaction $C^{12}(dp)C^{13}$ has been made with the cloud-chamber method of detection. The higher available energy of 3.2 Mev for bombardment, and hence longer proton range is an advantage since the range-energy relation operates in separating groups more than at low energies.

Several kinds of carbon targets were used. The first consisted of a thin (less than 1 mm air equivalent) layer of Aquadag on a gold foil.

A number-range curve plotted from these data involving several thousand tracks exhibited a definite asymmetry on the low energy side. However, other elements involving shorter and longer range contamination groups were also present as impurities. For that reason, these data were discarded. Final observations were made on purified CH_4 in the gas target cell. The sample kindly supplied by Professor Watson was estimated to contain less than 0.1 percent by volume of the usual impurities, O and N. With a pressure of 14 cm in the cell, the effective thickness of the target was 2 mm air equivalent. A series of diaphragms defining the beam and emerging protons made it impossible for any particle emitted from the walls to reach the cloud chamber directly. It should be noted that only about one-half of the width of the incident beam was used. Hence, the homogeneity in this case probably was somewhat better than shown in Fig. 2.

The results are depicted in Fig. 3. Tracks were grouped so that they ended in intervals of 3 mm. The group appears to be quite symmetrical with a width at half-maximum of 0.6 Mev in good

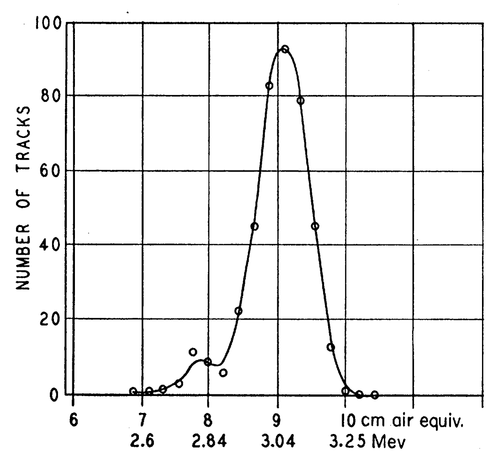

FIG. 2. Number-range distribution of deuterons scattered by a 1-mm air equivalent Au foil. Energy of beam = 3.2 Mev; beam current = 10^{-8} amp.

[4] M. C. Henderson and M. G. White, Rev. Sci. Inst. 9, 19 (1938).
[5] M. E. Rose and H. A. Bethe, Phys. Rev. 51, 205 (1937).
[6] J. R. Richardson, Phys. Rev. 53, 610 (1938); 55, 609 (1939).
[7] J. D. Cockcroft and W. B. Lewis, Proc. Roy. Soc. 154, 261 (1936).

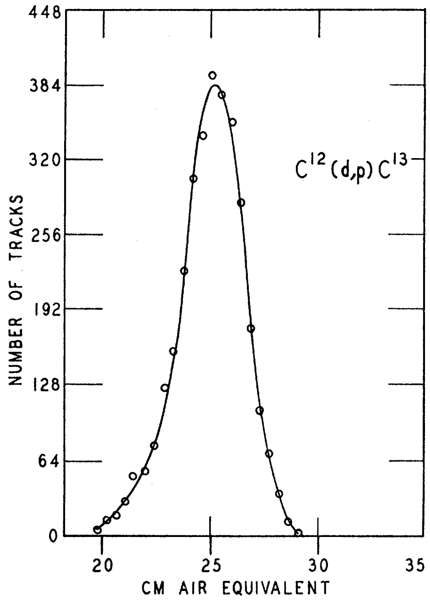

FIG. 3. Protons from carbon bombarded by deuterons. Target in the form of CH_4.

agreement with the work of Cockcroft and Lewis. If the group is a doublet and, a 2 : 1 ratio of intensities of the two components is assumed the separation must be much less than 285 kev. Richardson[8] has also looked for this fine structure and reported a negative result, although details of his work are not given. Watase and Itoh[9] have confirmed the existence of the 285-kev gamma-ray in the spectrum of N^{13}. However, in a private communication Dr. Itoh has kindly pointed out that he finds no indication of the 285-kev excited level in C^{13} from an analysis of the β-ray spectrum of N^{13}.

The curve shown in Fig. 3 does exhibit some asymmetry near the axis on the low energy side, with possibly a slight irregularity at 21.4 cm range. The latter may be accounted for by statistical fluctuations. The asymmetry noted may be connected with the weak low energy component in the deuteron beam. Some additional straggling introduced by the foil isolating the target cell from the cyclotron vacuum chamber, and small but finite target thickness are contributing factors.

Protons from Aluminum

The reaction $Al^{27}(dp)Al^{28}$ was first studied by McMillan and Lawrence[10] using an ionization chamber. Their results indicate the presence of five groups with possible intermediate groups that are unresolved. The cloud-chamber method just described has been applied to this problem in the hopes of obtaining higher resolution in the presence of a rather high neutron background from this element. A target of 1.4 mm air equivalent was employed. Tracks ending in 7-mm intervals were grouped together and the number plotted against range as shown in Fig. 4. Correction has been made for the variation of relative stopping power with energy in the aluminum foils[11] used to cause different groups to end successively in the chamber. Some adjustment was necessary to make the data taken with each additional foil join up with those preceding. However, the adjustment was small in each case, and thus the ordinates represent quite accurately the number of tracks actually observed.

The broad fluctuations in the curve may be taken to represent groups in rough agreement with the work of McMillan and Lawrence. However, there are indications that each may be complex, particularly in view of the large width. The end group appears to be complex and consist of at least three components. The fact that the curve does not drop to low or zero value, except possibly in the interval 66–70 cm also suggests a greater number than 5 groups. The authors feel that possibly these broad maxima do not involve individual levels in the Al^{28} residual nucleus, but on the other hand, represent regular fluctuations

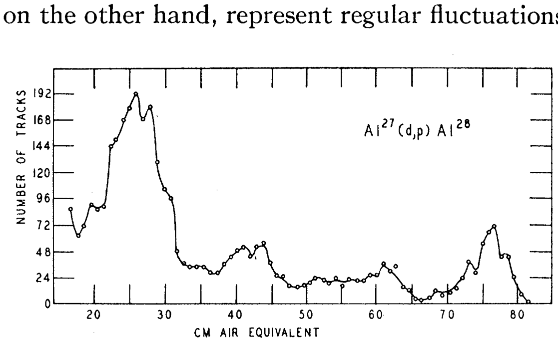

FIG. 4. Protons from a 1.6-mm air equivalent target of Al.

[8] T. R. Richardson, Phys. Rev. **55**, 1129A (1939).
[9] Y. Watase and J. Itoh, Proc. Phys. Math. Soc. Japan **21**, 389 (1939).
[10] E. McMillan and E. O. Lawrence, Phys. Rev. **47**, 343 (1935).
[11] 1.52 mg/cm^2 = 1 cm air.

in the density (per unit energy) of Al^{28} levels, thus giving the appearance of single groups. Similar tendencies have been noticed in unpublished experiments done at this laboratory on other elements in this mass range. However, in some cases (e.g. Ne and A) pronounced groups are observed where the minima between groups is low compared to the maxima in these groups. This may be taken as evidence for the assumption that the density of nuclear levels is not only a function of the total number of particles from a statistical viewpoint but also depends critically upon the characteristics of a given nucleus, i.e., to what degree the nucleus approximates a closed-shell configuration in neutrons and protons. It is of interest to recall the work of Plain, Herb, Hudson and Warren[12] who found a large number of levels from observations on the excitation function for γ-rays produced in the reaction $Al^{27}(p, \gamma)Si^{28}$.

In comparing the present results on aluminum with those of McMillan and Lawrence it appears that the relative intensity of the groups is different from that published by the above writers. Perhaps this discrepancy results from the fact that the present experiment was conducted at higher bombarding energies, the higher excitation being responsible for this difference in relative intensities. Similar effects have been noted by Pollard, Davidson and Schultz[2] in the case of boron bombarded by deuterons. More likely it is caused by the difference in technique of detection.

In conclusion, it is a pleasure to thank Professor Ernest Pollard for much valuable help and advice. The writers are also indebted to Dr. M. E. Rose for discussion. A grant from the George Sheffield Fund is gratefully appreciated.

[12] G. P. Plain, R. G. Herb, C. M. Hudson and R. E. Warren, Phys. Rev. **57**, 187 (1940).

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Protons from the Separated Isotopes of Carbon and Neon under Deuteron Bombardment

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The protons arising from the bombardment by 2.54-Mev deuterons of CH_4 gas enriched in C^{13} isotope and neon enriched in Ne^{22} have been studied with a cloud chamber. It is shown that the yield of long range protons from the $C^{13}(dp)C^{14}$ reaction is less than four percent of the yield of shorter range protons from the $C^{12}(dp)C^{13}$ reaction at this deuteron energy. This low yield means that the half-life of C^{14} discovered by Ruben and Kamen is considerably less than their estimate and is probably about 100 years. In neon the longest range group of protons discovered by Pollard and Watson is shown to be complex, with an indicated doublet width of the ground state of Ne^{21} of 0.44 Mev. The only proton group definitely indicated for the Ne^{22} bombardment occurs at about 30 cm range.

INTRODUCTION

RECENT improvements in the production of separated isotopes have immediate application to problems in nuclear physics. In studies of proton groups emitted in transmutations, samples enriched in one or more of the isotopes are necessary where: (1) Proton emission caused by the rare isotope is normally so small as to make detection difficult even in the absence of interfering groups from the more abundant isotopes; (2) the group caused by the rare isotope may be fairly strong but be overlapped by equally prominent groups from the abundant species. The transmutation of C^{13} by deuterons is an example of (1), while the situation in the case of neon may follow (2).

This paper presents the results of experiments on the protons from carbon enriched in C^{13} and on neon with and without enrichment in Ne^{22}. The cloud-chamber method of detection of

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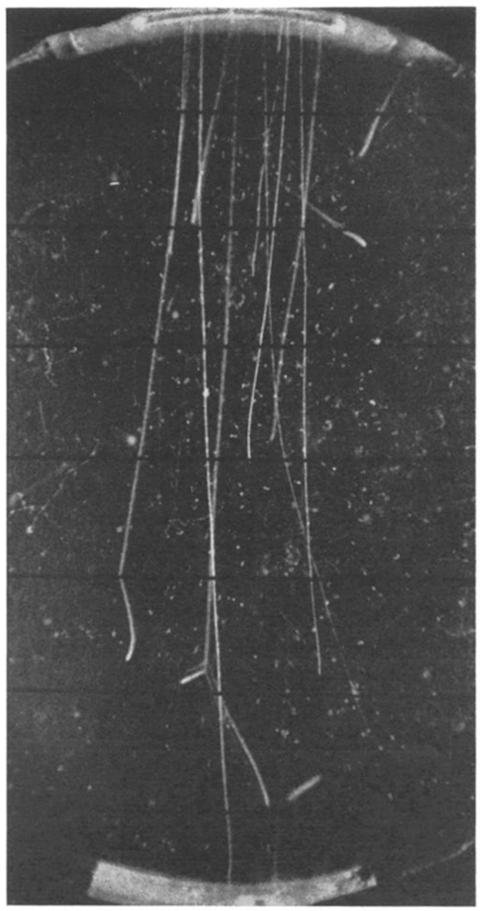

FIG. 1. Protons from aluminum bombarded by deuterons.