where L_B is the diffusion length in the detector. In these experiments $\rho=0.996$. It can also be shown that a similar correction for the finite size of the paraffin is entirely negligible.

The nuclear cross sections used in the calculations are given in Table II. In Table III are the derived constants to be substituted in Eqs. (1–3). By combining the rates of production observed for paraffin and for the mixtures, the individual rates of production were obtained. There are given[7] in Table IV. The value for carbon was calculated from that found for paraffin assuming that the hydrogen did not contribute and that the composition was C_nH_{2n}.

Owing to the absorption of the radiation responsible for neutron production in the paraffin and in the metal some correction should be applied to the rates observed directly. With the paraffin alone present 29 g/cm² of paraffin was above the detector. The aluminum added an additional 28 g/cm² and the lead 19.5 g/cm². An approximate correction has been made as follows. The variation of the number of neutrons with elevation corresponds to a mean free path[5] in air of about 150 g/cm². It was assumed that this mean free path varies as the cube root of the mass number of the nucleus. Thus for lead, for example, the value of 366 g/cm² was calculated. The observed rates were then multiplied by the appropriate absorption correction factors and the results are given in the last column of Table IV. The corrected rates are, of course, uncertain not only because of inaccuracies in the assumed absorption coefficients but also from the neglect of possible transition effects.

[7] In the preliminary account of the exponents given in reference 5, the value for aluminum was in error because of a numerical mistake.

PHYSICAL REVIEW VOLUME 81, NUMBER 4 FEBRUARY 15, 1951

Alpha-Particle Groups from the $N^{14}(d, \alpha)C^{12}$ and $N^{15}(d, \alpha)C^{13}$ Reactions*

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(Received October 26, 1950)

The alpha-particle groups from N^{14} and N^{15} targets bombarded with 1.4-Mev deuterons have been studied using a magnetic spectrometer. The Q-value for the $N^{14}(d, \alpha)C^{12}$ reaction is found to be 13.575 $\pm$0.012 Mev, and the energies of the excited states observed in C^{12} are 4.438$\pm$0.014 and 9.620$\pm$0.013 Mev. For the $N^{15}(d, \alpha)C^{13}$ reaction, the Q-value is measured as 7.681$\pm$0.006 with excited states in C^{13} at 3.083 $\pm$0.005 and 3.677$\pm$0.005 Mev.

I. INTRODUCTION

Among the various methods of exciting and studying the bound energy states of C^{12} and C^{13}, the $N^{14}(d, \alpha)C^{12}$ and $N^{15}(d, \alpha)C^{13}$ reactions have high Q-values, making them particularly suitable for investigating these nuclei over a wide range of excitation. The studies of the first reaction have shown[1,2] the presence of levels in C^{12} at 4.5 and 7.0 Mev, in general agreement with the results from other reactions. These results have recently been summarized by Hornyak, *et al.*[3] In the case of the $N^{15}(d, \alpha)C^{13}$ reaction, only the highest energy group of alpha-particles which is associated with the formation of C^{13} in the ground state has been observed.[1] With the objective of investigating these nuclei over a wider range of excitation, we have studied the alpha-particle groups emitted by thin targets containing N^{14} and N^{15} when bombarded with 1.4-Mev deuterons.

II. APPARATUS AND EXPERIMENTAL PROCEDURE

The experimental equipment has been described in previous papers.[4,5] Magnetic analysis was used both in the selection of the incident beam of deuterons of known energy and the investigation of the disintegration alpha-particles. The angle of observation was 90° with respect to the deuteron beam, and photographic detection was employed.

The energies of the observed alpha-particle groups were computed from measurements of the radii of curvature and the corresponding magnetic fields. The fields were measured with an analytical balance-type fluxmeter. The fluxmeter was calibrated on the basis of Brigg's value[6] for the Hr of RaC′ alpha-particles, from Lewis and Bowden's value[7] for the ratio of the

* This work has been assisted by the joint program of the ONR and AEC.
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[7] W. B. Lewis and B. V. Bowden, Proc. Roy. Soc. (London) **A145**, 250 (1934).

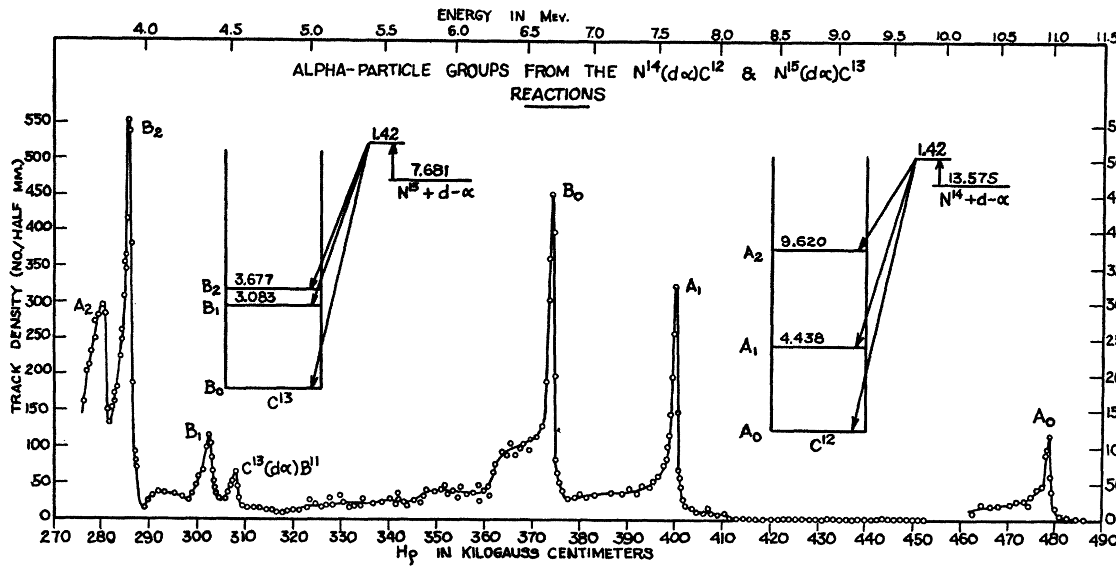

FIG. 1. Alpha-particle groups from tantalum-nitride target in which N^{14}:N^{15} ratio was 40:60. Energy of incident deuteron beam was 1.420 Mev.

velocities of these alpha-particles and polonium alpha-particles, and from measurements of the radius of curvature of polonium alpha-particles in the present analyzing magnet using a magnetic field of suitable strength. A value of 3.3159×10^5 gauss-cm for polonium alphas has been used in the calculations. In the conversion from the observed Hr values to the corresponding particle energies, a value[8] of 9652.2 emu/g has been used for the faraday. A similar fluxmeter has been used for the measurement of the fields of the magnet employed for deflecting the incident deuteron beam. This fluxmeter is calibrated from observations of the energy of the deflected deuterons after they have been scattered from thin foils.

Although we have often observed weak alpha-particle groups from the surface contamination of nitrogen on many targets, the low concentration of only 0.4 percent of N^{15} in normal nitrogen makes the use of such contamination layers impractical for studying the $N^{15}(d,\alpha)$ reaction. In the present work, the targets consisted of thin layers of tantalum nitride on tantalum, prepared as outlined in a previous paper.[5] For purposes of identifying the various groups observed, targets with both normal and enriched concentrations of N^{15} were used, together with observations on the changes in energy of the groups as the incident deuteron energy was varied. Surface contaminations on these targets were eliminated to a large extent by maintaining the targets at a dull red heat during bombardment. The thickness of those surface layers not removed in this way was determined from comparisons of the energy of one of the alpha-particle groups from the heated targets with that of the same group from a freshly prepared target consisting of a thin deposit of ammonium nitrate on platinum. Appropriate corrections for the effects of these surface layers were made in all of the measured particle energies. In no case was the correction more than 10 kev.

A disadvantage of the tantalum-nitride targets is that the nitrogen is not confined solely to a thin surface layer but appears to be present in small amounts to a considerable depth in the tantalum. Thus, there is associated with each group of alpha-particles a number of lower energy particles, which, together with those from $N^{14}(d,2\alpha)Be^8$, lead to a background between the observed peaks. A correction for the effects of this background was made when determining the radius of curvature of each group. An analytical correction to the measured radii of curvature was made for the small effects due to the finite acceptance angle of the nuclear-track plates and to the fact that the particles are emitted from a line rather than from a point source on the target.

III. RESULTS

In these experiments, each photographic plate was exposed at a fixed field strength and thus recorded an interval in the momentum spectrum of the charged particles emitted from the target. The alpha-particle groups shown in Fig. 1 were observed from an unheated tantalum-nitride target in which the N^{15} concentration was approximately 60 percent of the total nitrogen content. The results were obtained from a number of plates exposed at different magnetic fields so as to cover the range of alpha-particle energies from 3.5 to 11.5 Mev. The incident deuteron energy was 1.420 Mev, and the field strengths were so chosen that the regions covered by each plate overlapped slightly. Separate plates were taken on each of the observed groups using heated targets in order to minimize the effects of surface layers

[8] J. W. M. DuMond, Phys. Rev. **77**, 411 (1950).

TABLE I. Data on $N^{14}(d, \alpha)C^{12}$.

Group	Q-value for $N^{14}(d, \alpha)C^{12}$ (in Mev)	Level in C^{12} (in Mev)
A_0	13.575±0.012	0
A_1	9.137±0.006	4.438±0.014
A_2	3.955±0.003	9.620±0.013

on the measured energies. The weak group at 308 kgauss-cm has been identified from other experiments as arising from carbon contamination and was not observed from the heated targets.

Three of the groups shown in Fig. 1 have been identified as arising from the $N^{14}(d, \alpha)C^{12}$ reaction. These are labeled A_0, A_1, and A_2. The Groups A_0 and A_1 have been observed previously[1,2] and correspond to transitions to the ground state and the first excited state of C^{12}. The A_2 group has not been reported by other observers, although the level in C^{12} at 9.7 Mev to which it corresponds is well known from studies of other reactions.[3] The measured Q-values for these groups are 13.622, 9.137, and 3.955 Mev.

We have considerable evidence that, at the high magnetic fields required for deflecting the A_0 group, the measured field strengths may be too high by approximately 0.1 percent. At these high fields, the iron of the magnet is close to saturation, and it appears that in this region the field at the position of the fluxmeter is not accurately proportional to that in which the particles are focused. This effect is probably associated with small irregularities in the magnet core. Consequently, we believe that a more precise value for the Q-value for the ground-state group A_0 is obtained by adding our measured Q-values for the $N^{14}(d, p)N^{15}$ and the $N^{15}(p, \alpha)C^{12}$ reactions. These are 8.615±0.009 and 4.960±0.007 Mev, respectively.[5,9] This cycle leads to a value of 13.575±0.012 Mev for the $N^{14}(d, \alpha)C^{12}$ reaction. The difference of 47 kev between this value and that directly measured is closely of the amount and in the direction to be expected from our measurements on the saturation effects in the magnet.

A similar value for the $N^{14}(d, \alpha)C^{12}$ reaction is obtained from the consideration of other cycles. Thus, using a value of 7.681±0.009 from the present paper for $N^{15}(d, \alpha)C^{13}$, 2.716±0.005 for $C^{12}(d, p)C^{13}$, and 8.615±0.009 Mev for $N^{14}(d, p)N^{15}$, we obtain 13.580 ±0.015 Mev. Additional confirmation of this value is obtained from the measured energy of the first excited state of C^{12} from the $N^{15}(p, \alpha)$ reaction. Schardt has measured the Q for the short-range alpha-particles from this reaction[3] as 0.529±0.008 Mev, while we find 4.960 ±0.007 for the ground-state group. These two values give 4.431±0.011 Mev for the first level in C^{12}, in agreement with measurements on the gamma-radiation from this level. This energy when added to the Q for the A_1 group which is associated with the same level leads to 13.568±0.012 Mev for $N^{14}(d, \alpha)C^{12}$.

[9] Strait, Van Patter, Buechner, and Sperduto (to be published).

The present results on this reaction are summarized in Table I.

Previous work on this and other reactions[3] indicates a level in C^{12} at approximately 7 Mev. Recently, from studies of the $Be^9(\alpha, n)$ reaction, Guier and Roberts[10] have also found groups which they attribute to this level and to one at 7.9 Mev. If these levels were excited in the present reaction, the corresponding alpha-particle groups would be observed in the region between 330 and 350 kgauss-cm. As can be seen in Fig. 1, there is no evidence for peaks in this region, although the alpha-particle background might obscure any weak groups if such were present. Since the reported groups corresponding to these levels have been of low intensity, it is probable that the levels would not be observed in the present work.‡

The alpha-particle groups arising from the $N^{15}(d, \alpha)C^{13}$ reaction are labeled B_0, B_1, and B_2 in Fig. 1. While only the B_0 group has been previously reported,[1] the excited states in C^{13} to which these groups correspond are well known from studies of other reactions. The Q-values for the groups measured in the present work are tabulated in Table II, together with the excited levels in C^{13} with which they are associated.

While these values for the levels in C^{13} are in general agreement with the results from other reactions,[3] the value for the first level observed in these experiments is somewhat lower than the value of 3.098±0.008 which we have reported[11] from the $C^{12}(d, p)C^{13}$ reaction. Recently we have remeasured this reaction in the light of improved values for certain geometrical and other factors. The more recent Q-value for this reaction is 2.716±0.005 Mev for the ground-state group. This leads to a value of 3.086±0.005 Mev for this level when measured from the $C^{12}(d, p)C^{13}$ reaction, in good agreement with that obtained in the present work.

It is interesting to note that, as in the previous work of Heydenburg, Inglis, Whitehead, and Hafner[12] and the work in this laboratory[11] on $C^{12}(d, p)C^{13}$, the data in Fig. 1 show no evidence for a group which would correspond to a level in C^{13} in the region from 0.8 to 1.0 Mev. Such a level has often been reported from the

TABLE II. Data on $N^{15}(d, \alpha)C^{13}$.

Group	Q-value (in Mev)	Level in C^{13} (in Mev)
B_0	7.681±0.006	0
B_1	4.598±0.004	3.083±0.005
B_2	4.004±0.003	3.677±0.005

[10] W. H. Guier and J. H. Roberts, Phys. Rev. **79**, 719 (1950).

‡ *Note added in proof:* Recently, Terrell has studied the gamma-radiation from $Be^9(\alpha,n)C^{12*}$ using a pair spectrometer [Phys. Rev. **80**, 1076 (1950)]. His work shows that, if a level in C^{12} at 7 Mev is excited in this reaction, the gamma-radiation associated with it has an intensity less than one-half percent that from the 4.44-Mev level in C^{12}.

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

[12] Heydenburg, Inglis, Whitehead, and Hafner, Phys. Rev. **75**, 1147 (1949).

$B^{10}(\alpha, p)C^{13}$ reaction; and, although the recent study of this reaction by Creagan[13] failed to show such a group, the result may not be definite, since this work also failed to show the well-known 3.1-Mev level. More recently, Berlman, using 10-Mev deuterons, has reported[14] a proton group from the $C^{12}(d, p)C^{13}$ reaction that leaves C^{13} in a 1.0-Mev excited state. If a level between 0.8 and 1.0 Mev were excited in the present reaction, the alpha-particle group would appear in the region between 355 and 360 kgauss-cm. While the background in this region would obscure weak groups, we conclude that, if such a level is excited, the intensity is less than 0.1 that of the ground-state transition.**

The measured half-widths of the alpha-particle groups in Fig. 1 have been compared with the half-widths that would be expected if the broadening of the lower energy peaks were due entirely to the effects of target thickness. The measured and computed half-widths are in reasonable agreement except for the $N^{14}(d, \alpha)C^{12}$ group labeled A_2. As can be seen from Fig. 1, the half-width of this group is nearly twice that of group B_2, which has nearly the same energy and which appeared on the same nuclear-track plate. Since there is no reason to expect a difference between the effective thicknesses of the TaN^{14} and TaN^{15} layers on the enriched target, it is believed that this increased width is not an instrumental effect. Although it is possible that the group A_2 actually consists of two closely spaced groups which were not resolved,§ it is to be noted that when C^{12} is in the 9.62-Mev excited state, a transition to Be^8 plus an alpha-particle is energetically possible. The possibility of this alternative mode of decay for this state may contribute to the width of the A_2 group.

In the recent work of Guier and Roberts[10] on the $Be^9(\alpha, n)C^{12}$ reaction, the neutron group associated with the 4.4-Mev level in C^{12} was found to have considerable breadth, and it was suggested that this level might not be single. The width of the peak A_1 in Fig. 1 suggests that such structure is not present in the level excited in the $N^{14}(d, \alpha)C^{12}$ reaction at the bombarding energies used in this work.

We are indebted to our colleagues in the High Voltage Laboratory for much helpful discussion and assistance. We are particularly grateful to Mrs. C. Bryant and Mr. W. A. Tripp for their careful measurements on the photographic plates.

[13] R. J. Creagan, Phys. Rev. **76**, 1769 (1949).

[14] I. B. Berlman, Phys. Rev. **79**, 411 (1950).

** Very recently, Blundell and Rotblat [Phys. Rev. **81**, 144 (1951)] have reported that their studies of the $C^{12}(d, p)C^{13}$ reaction using 8-Mev deuterons show no evidence of a level in C^{13} between the ground state and the 3.11-Mev state, and they suggest that the proton group reported as associated with a 1-Mev level in C^{13} may be due to oxygen contamination.

§ Since this manuscript was submitted for publication, we have learned from R. G. Thomas in a private communication that Rotblat has recently reported studies of $C^{12}(d, p)C^{13}$ which show a level in C^{13} at 3.9 Mev in addition to those at 3.1 and 3.7. In the present experiments, a level at 3.9 Mev would lead to an alpha-particle group at 280 kgauss-cm. From the variation of the yield of peak A_2 (Fig. 1) with the percentages of N^{14} and N^{15} in the targets, we conclude that no intense group corresponding to a 3.9-Mev level in C^{13} is present. However, the possibility of a weak group in this region from the $N^{15}(d, \alpha)C^{13}$ reaction cannot be excluded, and it is possible that the unexpected width of the A_2 peak arises from such a group. If this is the case, the Q-value reported here for the A_2 group and the corresponding level in C^{12} may be somewhat in error, the amount depending on the intensity and location of the other group.