Transmutations of Nitrogen by Deutons

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Nitrogen bombarded by deutons emits three alpha-particle and two proton groups. For deutons of maximum energy 1.4 mv traversing an air target the alpha-particle groups have ranges of 6.9, 7.8 and 12.7 cm. The reaction involved is $N^{14}+D^2 \rightarrow C^{12}+He^4$, and the transmutation energy, derived from the long range group, in conjunction with the precise mass spectrograph determinations of D^2, He^4 and C^{12} yields for the mass of N^{14} the value 14.0069. The 6.9 and 7.8 cm groups indicate the existence of excited levels in C^{12} at 3.8 and 4.7 mv. The proton groups from a thin air target bombarded by 1.25 mv deutons have ranges of 24 and 85 cm. The reaction involved is $N^{14}+D^2 \rightarrow N^{15}+H^1$. The transmutation energy of this reaction yields for the mass of N^{15} the value 15.0041. The 24 cm group indicates an excitation level in N^{15} at 4.7 mv. For 1.2 mv deutons, the effective nuclear collision cross sections for the alpha-particle and proton reactions are about 10^{-27} cm^2 and 3×10^{-29} cm^2, respectively.

INTRODUCTION

In experiments in our laboratory,[1] which were in the nature of a preliminary survey of nuclear reactions induced by deutons and protons, there was noted a particularly strong emission of alpha-particles of about 6.8 cm range from a target of NH_4NO_3 bombarded by 1.2 mv deutons. The absence of this alpha-particle group from other targets containing oxygen indicated that nitrogen was the element involved in the reaction. In those early experiments the emission of protons and neutrons from the nitrogen target was also observed.[2] Meanwhile Livingston and McMillan[3] have found that radio-oxygen is formed when nitrogen is bombarded by deutons, the reaction involved being the one in which neutrons are emitted.

We have lately carried out a more detailed investigation of the reactions of deutons with nitrogen, which confirms and extends the earlier observations, and this is the subject of the present paper.

APPARATUS

In these experiments a beam of 2.2 mv deutons was brought out from the larger of our instruments for the acceleration of ions through an aluminum window (1 cm stopping power) into the air. The air itself provided a convenient nitrogen target. Observation of the blue glow produced by the deuton beam in the air furnished immediate and reliable evidence of the homogeneity and range of the deutons.

In Fig. 1 is shown the arrangement of slits for defining the deuton beam and collimating the emitted particles from a thin target of air. The arrangement is ideal in two respects. The use of an essentially thin target made it possible to resolve proton or alpha-particle groups near in range, and the possibility of contaminations from the walls or target support is not present. All observed radiations excepting the neutrons and gamma-rays necessarily come from the air, as the beam nowhere impinges on anything but air within sight of the recording ionization chamber. The radiations were recorded as usual with a shallow ionization chamber (4 mm deep) and a linear amplifier, in conjunction with a cathode-ray oscillograph and Wynn-Williams thyratron recording mechanism. Visual observations with the cathode-ray oscillograph provided a con-

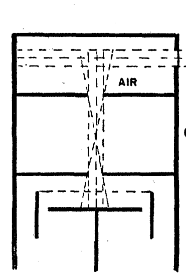

FIG. 1. Arrangement of slits defining the gas target and the beam of disintegration particles recorded by the Wynn-Williams ionization chamber.

[1] G. N. Lewis, M. S. Livingston and E. O. Lawrence, Phys. Rev. **44**, 55 (1933).
[2] E. O. Lawrence and M. S. Livingston, Phys. Rev. **45**, 220 (1934).
[3] M. S. Livingston and E. McMillan, Phys. Rev. **46**, 437 (1934).

tinuous indication of the nature of the ionizing particles recorded, while by altering the bias on the thyratrons, the protons could be distinguished from the alpha-particles.

Alpha-Particles

For the observation of the alpha-particles 12 mm slits 3 cm apart were used, the first slit being one cm from the deuton beam. The air target thus had an effective thickness of about 1.5 cm, and since the deutons traversed 1.5 cm of air after passing through this region, the effective energy of the bombarding deutons varied from 1.4 mv to 0.85 mv across the target. With a high bias on the thyratrons, only alpha-particles and heavy neutron recoil nuclei were recorded. The bias used in these experiments for the alpha-particle observations was about three times that used for the proton measurements. By visual observations with the cathode-ray oscillograph it was quite easy to distinguish the alpha-particles from the neutron recoils because the alpha-particles gave ionization pulses of more or less constant amounts, while the recoil nuclei gave pulses over a wide range of values, larger and smaller.

The ranges of the particles were determined in the usual way by placing absorbers between the ionization chamber and the target. This was accomplished both by simply moving the chamber back from the slits and using the air itself as an absorber, and by interposing 0.001 inch aluminum foils. Calibration of the foils in previous experiments using the alpha-particles from lithium showed that 0.001 inch aluminum has a stopping power of almost exactly 4 cm of air.

The alpha-particle observations are shown in Fig. 2. The ordinates record the actual number of observed counts per second per microampere of bombarding deutons striking the aluminum window, as a function of absorber thickness in equivalent cm of air (20°C, 760 mm). The aluminum window was mounted on a grid so that the actual bombarding current in the air was somewhat less, perhaps half as much. Because of the large alpha-particle emission, the bombarding currents used were only a few hundredths of a microampere. For absorbers less than 12.5 cm, the alpha-particle counts greatly outnumbered those produced by neutron recoils, and the data in Fig. 2 may be regarded as entirely due to the former.

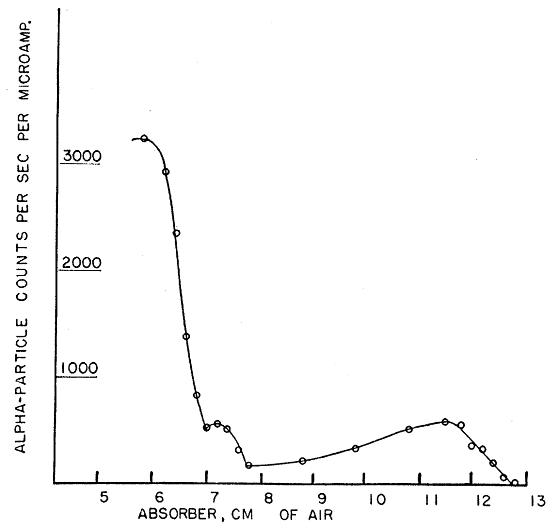

Fig. 2. Range distribution of alpha-particles from a 15 mm thickness of air bombarded by 1.4 mv deutons.

It is seen that there are three alpha-particle groups of ranges 12.7 cm (11.2 mv), 7.8 cm (8.3 mv) and 6.9 cm (7.7 mv). We made observations in the region below 5.5 cm, and obtained evidence of another alpha-particle group of shorter range, but we wish to examine this region more closely before presenting any evidence.

The shortest range group, which is by far the most intense, agrees with our earlier preliminary observations[1] using an NH_4NO_3 target. However, to make more certain that all three alpha-particle groups are due to the reaction of the deutons with nitrogen, the alpha-particle observations were repeated with the air replaced by oxygen. The alpha-particle counts with oxygen were less than 1 percent of those from the air and those that were obtained were evidently neutron recoils.[4] Thus the alpha-particles observed are to be ascribed to nitrogen.

[4] With illuminating gas, rather than oxygen in place of the air, we obtained a very large number of counts, more than from the air itself. In this case also visual observations with the cathode-ray oscillograph showed that the ionization pulses were due to neutron recoil nuclei in the ionization chamber, indicating a copious emission of neutrons from a constituent of the illuminating gas, which was

The reaction here involved doubtless is

$$N^{14}+D^2\rightarrow C^{12}+He^4.$$

The longest range group of alpha-particles almost certainly corresponds to the case where the entire energy released in the reaction is in the form of kinetic energy of the alpha-particle and the recoil carbon nucleus. The energy released in the transmutation, called henceforth the transmutation energy, is readily calculated from the observed energy of the long range alpha-particles, taking account of the maximum energy of the deutons, 1.4 mv, and momentum considerations involved in the recoil of the carbon nucleus. Thus it is calculated that the transmutation energy is 13.7 mv, corresponding to a loss of mass in the reaction of 0.0147 mass units. All of the masses involved in this reaction have been measured with the mass spectrograph. Because D^2, He^4 and C^{12} have all been measured with great precision, greater than that of N^{14}, this datum may be used for an evaluation of the mass of N^{14} of comparable precision, thus,

$$\begin{aligned}N^{14} &= C^{12}+He^4-D^2+(\text{transmutation energy})\\ &=12.0036+4.0022-2.0136+0.0147\\ &=14.0069.\end{aligned}$$

This value agrees satisfactorily with that of Aston,[5] 14.008, and Bainbridge's[6] later determination, 14.0074.

The 6.9 and 7.8 cm alpha-particle groups presumably are emitted with the C^{12} nucleus (or the alpha-particle) left in an excited state in each case. The total kinetic energy of the alpha-particles and the recoil nuclei in excess of the kinetic energy of the bombarding deuton is calculated to be 9.0 and 9.9 mv for the two groups. Thus it appears that there are two gamma-ray levels in C^{12}, one of 3.8 mv and another of 4.7 mv, though of course the possibility that one (or both) of the levels belongs to the alpha-particle cannot be excluded.

Although we have some evidence that gamma-rays are emitted from a nitrogen target under deuton bombardment, we have not examined the question carefully as yet, and have not established that these gamma-rays have energies corresponding to these alpha-particle groups. There is, however, independent evidence of these excitation levels. Bothe and Becker[7] have observed by means of coincidence Geiger counters the emission of a 5 mv gamma-ray from beryllium bombarded by alpha-particles. This gamma-ray presumably comes from excited C^{12} formed with the emission of a neutron. Crane and Lauritsen[8] have observed the gamma-rays from boron bombarded by deutons. By measuring the curvature of electron and positron tracks produced by the gamma-rays in a Wilson chamber placed in a magnetic field, they have obtained evidence for at least four gamma-rays of 2.4, 4.2, 5.6 and 6.7 mv energy. Crane, Delsasso, Fowler and Lauritsen have identified their 5.6 mv gamma-ray with the 5 mv gamma-ray of Bothe and Becker, both being ascribed to the same excitation level of C^{12}. It is possible that the 4.7 mv energy derived from the present data represents another measure of the same energy level.

On the assumption that the alpha-particle emission is isotropic, it is readily calculated from the data of Fig. 2, taking account of the geometry of the slit system, that about one alpha-particle was emitted from the 15 mm thickness of air for every 10^7 deutons, having an average energy crossing the air target of 1.15 mv. Taking account of the number of nitrogen atoms in this thickness of air, this transmutation yield may be expressed in terms of an effective cross section for transmutation, which is 10^{-27} cm^2, or a corresponding effective radius of about 2×10^{-14} cm. This value is small compared to the nuclear radius deduced from scattering experiments. In other words, the chance of transmutation in a close collision is small.

Protons

The range distribution of the protons emitted from the air target is shown in Fig. 3. Here the bias in the thyratron counter is such that only

doubtless carbon. That carbon emits neutrons under deuton bombardment was shown in our first experiments with deutons (M. S. Livingston, M. C. Henderson and E. O. Lawrence, Phys. Rev. **44**, 781 (1933)), and more recently it has been established that these neutrons are emitted in the reaction in which radio-nitrogen is formed.

[5] F. W. Aston, Proc. Roy. Soc. **A115**, 503 (1927).

[6] Unpublished. We wish to thank Dr. Bainbridge for communicating to us directly this recent measurement.

[7] W. Bothe and H. Becker, Zeits. f. Physik **76**, 421 (1932).

[8] H. R. Crane, L. A. Delsasso, W. A. Fowler and C. C. Lauritsen, Phys. Rev. **46**, 1109 (1934).

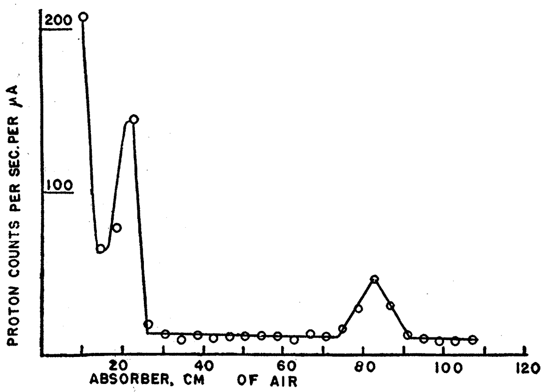

FIG. 3. Range distribution of protons from 15 mm air target bombarded by 1.4 mv deutons.

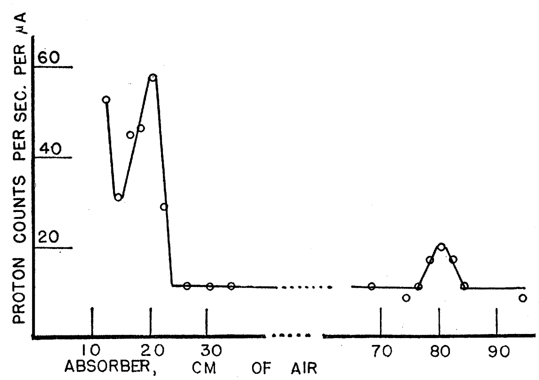

Fig. 4 Range distribution of protons from 5 mm air target bombarded by 1.25 mv deutons.

those protons were counted that were within a few centimeters of the end of their range. Again deutons of energies between 0.85 and 1.4 mv bombarded an air target of 15 mm thickness, the same geometry of slits being used as was employed in the alpha-particle observations. There are two distinct proton groups of ranges 91 and 26 cm. The counts observed at shorter range are due to the alpha-particles. When the air was replaced[9] by oxygen, these two proton groups disappeared. This observation is consistent with those of Cockcroft and Walton,[10] who ascribed to oxygen 4 and 8 cm proton groups, and of Rutherford and Oliphant,[11] who have come to the conclusion that an 8 cm group arises from bombardment of oxygen by deutons. The 91 and 26 cm groups are therefore to be ascribed to nitrogen, and presumably are involved in the reaction

$$N^{14}+D^2 \rightarrow N^{15}+H^1.$$

In order to examine more carefully the homogeneity and range of these two proton groups, the slits defining the width of the air target and the angular divergence of the disintegration protons collected by the ionization chamber were narrowed to 3.5 mm, the slits being as before 3 cm apart, at right angles to the deuton beam. With this very narrow air target and very small spread in solid angle of the disintegration protons arriving at the ionization chamber, and with the thyratron bias voltage such that only those protons that were within 2 cm of their range were recorded, the counts shown in Fig. 4 were obtained. The two proton groups show themselves sharply[12] and distinctly above the uniform background due to the neutrons.[13]

With the narrower slits the energy of the deutons when passing across the thinner air target varied from 1.25 to 1.05 mv. The sharpness of the proton groups was quite consistent with this spread in energies, thus indicating that the groups are homogeneous, to a high degree, with maximum ranges of 24 cm (4.1 mv) and 85 cm (8.5 mv). Again the long range group is doubtless emitted in the reaction in the case when all of the energy released is converted into kinetic energy. The 85 cm protons correspond to a transmutation energy of 8.0 mv (0.0086 mass

[9] With illuminating gas in place of the air, a very large emission of protons was observed, having ranges as great as 90 cm. These long range protons, which are probably emitted in the formation of C^{13}, in which the whole transmutation energy is given to the emitted proton, are being investigated in detail and will be reported later.

[10] J. D. Cockroft and E. T. S. Walton, Proc. Roy. Soc. **A144**, 704 (1934).

[11] Lord Rutherford and M. L. E. Oliphant, mentioned by Cockcroft and Walton, reference 10.

[12] The homogeneous long range group obtained in this way has been found to be very useful in checking the performance of the ionization chamber-linear amplifier combination, that is, in finding out what range of proton energies is counted by the apparatus for any given bias voltage. Later on we hope to use this group in measurements on the Bragg ionization curve for protons, as there seems to be some uncertainty about this matter at the present time.

[13] The neutrons which gave rise to the counts with absorbers between 25 and 75 cm and also beyond 90 cm, were due in part to the nitrogen reaction in which radiooxygen is formed,[3] and in part to the aluminum and carbon (wax) of the window through which the deuton beam emerged from the vacuum chamber.

units). This datum may be used to evaluate the mass of N^{15} as follows:

$$N^{15}=N^{14}+D^2-H^1-(\text{transmutation energy})$$
$$=14.0069+2.0136-1.0078-0.0086$$
$$=15.0041.$$

This is to be compared with the value derived from band spectra data by Birge and Menzel[14] of 15.0032.

The 24 cm proton group corresponds to a kinetic energy release in the reaction of 3.3 mv, and the obvious interpretation is that when these protons are emitted, N^{15} is left in a 4.7 mv excitation level.

The experimental observations indicate that about a thirtieth as many protons as alpha-particles are emitted from nitrogen. In other words, the effective collision radius for the formation of N^{15} is about 4×10^{-15} cm.

The fact that the alpha-particle emission is considerably greater than the proton emission may be interpreted to indicate that the nuclear barrier (of C^{12}) for alpha-particles is less than the energy with which they are released (8 mv). This is quite in accord with the estimate of 3.6 mv for the nuclear barrier of carbon deduced from scattering experiments, as given by Pollard.[15]

These experiments have been aided by grants from the Research Corporation and the Chemical Foundation.

[14] R. T. Birge and D. H. Menzel, Phys. Rev. **37**, 1669 (1931).

[15] E. W. Pollard, Phil. Mag. **16**, 1131 (1933).

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Note on the Scattering of X-Rays from Fluids Containing Polyatomic Molecules

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The intensity of the (unmodified) scattered radiation from a fluid containing one kind of molecules is given by:

$$S=(1/\Sigma_n Z_n)\left[F_1^2+F_2^2\int P_{(R)}dR(\sin kR)/kR\right],$$

where $F_1^2=\Sigma_n\Sigma_m f_n f_m(\sin kr_{nm})/kr_{nm}$, while F_2^2 depends both upon the molecular structure and upon the relative orientation of the molecules. It is shown that the radial distribution function P_R may be obtained directly from the observed scattering curve if the molecular structure is known:

$$P_{(R)}=4\pi R^2\rho_0+\frac{2R}{\pi}\int_0^\infty k\left[\frac{S\Sigma_n Z_n}{F_1^2}-1\right]\frac{F_1^2}{F_2^2}\sin(kR)dk,$$

where ρ_0 is the density of the fluid in molecules per unit volume.

When x-rays are scattered from a fluid containing only one kind of atoms (strictly speaking we should require the atoms to be equivalent as well), the intensity of the (unmodified) scattered radiation is given by[1]

$$S=(f^2/Z)\left[1+\int 4\pi r^2\rho_0 w_{(r)}dr(\sin kr)/kr\right], \quad (1)$$

where S is the intensity expressed in terms of the Thomson scattering. Z is the atomic number, f the scattering power of the atom and $k=4\pi\sin\theta/\lambda$. $4\pi r^2\rho_0 w_{(r)}dr$ (where ρ_0 is the density of the fluid in atoms per unit volume) represents the probability of finding an atom at a distance between r and $r+dr$ from any given one. As shown by Zernike and Prins[2] and by Debye and Menke[1], the radial distribution function may be obtained directly from the observed scattering curve, the result being:

[1] P. Debye and H. Menke, Ergebn. d. Techn. Röntgenkunde **2**, 1 (1931); compare also reference 2.

[2] Zernike and Prins, Zeits. f. Physik **41**, 184 (1927).