THE

PHYSICAL REVIEW

A journal of experimental and theoretical physics established by E. L. Nichols in 1893

SECOND SERIES, VOL. 80, No. 5 DECEMBER 1, 1950

Proton Groups from the $N^{14}(d, p)N^{15}$ and $N^{15}(d, p)^{16}$ Reactions*

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(Received July 26, 1950)

The proton groups from nitrogen targets bombarded with deuterons have been investigated with a magnetic spectrometer. Seven groups have been identified as arising from the $N^{14}(d\ p)N^{15}$ reaction with Q-values of 8.615±0.010; 3.339±0.005; 3.310±0.005; 2.287±0.005; 1.451±0.005; 1.306±0.005; and 0.300±0.005. One group has been found which is assigned to $N^{15}(d,p)N^{16}$ with $Q=-0.034\pm0.005$ Mev.

I. INTRODUCTION

THE proton groups from the $N^{14}(d,p)N^{15}$ reaction have been the subject of numerous investigations, the most complete being those of Guggenheimer, Heitler, and Powell[1] and of Wyly.[2] Guggenheimer and his co-workers bombarded gaseous nitrogen targets with 6.5-Mev deuterons. They observed proton groups with Q-values of 8.55, 3.5, 2.5, 1.3, and 0.3 Mev, indicating energy levels in N^{15} at 5.0, 6.0, 7.2, and 8.2 Mev. The 7.2 and 8.2 levels were believed to be doublets from evidence provided by the variation with angle of the intensities of the groups. Since the photographic-detection technique used in these experiments allowed an energy resolution of somewhat less than 0.3 Mev for proton groups in the range from 2 to 13 Mev, it is probable that the spacing of these doublets is of the order of 100 kev. The work of Wyly has confirmed the existence of the lower-energy groups. Wyly obtained Q-values of 8.61, 3.29, 2.30, and 1.40 Mev, indicating levels in N^{15} at 5.32, 6.31, and 7.21 Mev. He also found indications that the 7.21 level is a doublet.

Recently, Kinsey, Bartholomew, and Walker[3] have used a pair spectrometer to investigate the gamma-rays from the $N^{14}(n,\gamma)N^{15}$ reaction. Their results lead to the following values for energy levels in N^{15}: 5.287±0.010; 6.318±0.010; 7.164±0.010; 7.356±0.012; 8.278±0.16; 9.156±0.30. The 7.356- and 7.164-Mev levels probably correspond to the 7.2-Mev doublet reported by Guggenheimer *et al.* and by Wyly.

There is considerable variation among the values for the Q of the $N^{15}(d,p)N^{16}$ reaction which can be calculated from published measurements. Wyly investigated this reaction directly, using normal and enriched ammonia targets. By normalizing his data, and subtracting the normal-target data from the enriched-target data, he obtained a proton group corresponding to a Q-value of 0.23±0.15 Mev for this reaction. Measurements of the Q-value of the $F^{19}(n,\alpha)N^{16}$ reaction by Bleuler and Rossel[4] and by Jelley and Paul[5] indicate ground-state values for the $N^{15}(d,p)N^{16}$ reaction of 1.1±0.3 Mev and 0.7±0.9 Mev, respectively. Measurements on the maximum energy of the beta-particles from N^{16} by Sommers and Scherr[6] and by Bleuler, Sherrer, Walter, and Zunti[7] give 0.6±0.5 Mev and 0.3±0.8 Mev, respectively, for the $N^{15}(d,p)N^{16}$ reaction. In addition, Szelenyi[8] has calculated the mass of N^{16} using interpolation in a plot of mass-defect differences, and the value obtained indicates a Q-value for this reaction of 1.1±0.7 Mev.

With a view toward obtaining further information regarding the $N^{14}(d,p)N^{15}$ and $N^{15}(d,p)N^{16}$ reactions, we have used a high-resolution magnetic spectrometer to study the protons emitted from nitrogen targets bombarded with deuterons.

* This work has been assisted by the joint program of the ONR and AEC.
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[1] Guggenheimer, Heitler, and Powell, Proc. Roy. Soc. **A190**, 196 (1947).
[2] L. D. Wyly, Phys. Rev. **76**, 316 (1949).
[3] Kinsey, Bartholomew, and Walker, Phys. Rev. **77**, 723 (1950).
[4] E. Bleuler and J. Rossel, Helv. Phys. Acta **20**, 445 (1947).
[5] J. V. Jelley and E. B. Paul, Proc. Roy. Soc. **63A**, 122 (1950).
[6] H. S. Sommers, Jr., and R. Scherr, Phys. Rev. **69**, 21 (1946).
[7] Bleuler, Sherrer, Walter, and Zunti, Helv. Phys. Acta **20**, 96 (1947).
[8] T. Z. Szelenyi, Phys. Rev. **75**, 1105 (1950).

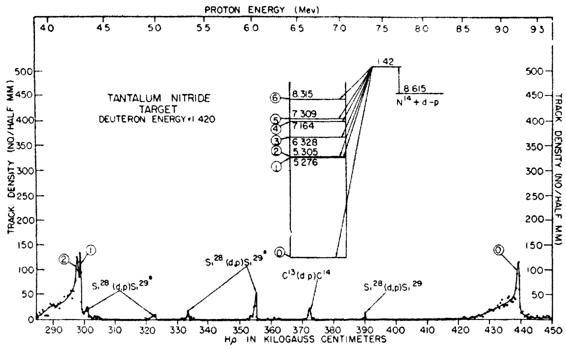

FIG. 1. Proton groups with energies between 4.0 and 9.5 Mev from tantalum-nitride target bombarded by deuterons.

II. APPARATUS AND EXPERIMENTAL PROCEDURE

The apparatus and experimental procedure were essentially the same as those described in a previous paper.[9] The deuteron beam from an electrostatic generator was sharply defined in space, direction, and momentum by means of a slit arrangement and magnetic analysis. The target was located in the annular gap of a large annular magnet, in which the magnetic field was parallel to the direction of the incident beam. A fraction of those particles emitted in the plane normal to the incident beam was focused by the 180-degree focusing action of the uniform magnetic field in the annular gap and were detected with Eastman *NTA* nuclear-track plates. These plates were also located in the annular gap in a position diametrically opposite to that of the target and were inclined at an angle of 20 degrees with respect to the direction of the observed particles. From measurements of the magnetic field and the radii of curvature, the momentum of the particles could be computed.

The magnetic field in the annular region was measured with a fluxmeter consisting of a small current-carrying coil rigidly attached at the center of an analytical balance. When the small coil was placed in a magnetic field it experienced a torque which was proportional to the product of the field intensity and the current through the coil. In practice, by the adjustment of the current through the coil, a balance was achieved between this torque and a constant mechanically applied torque. The calibration constant for the fluxmeter was determined from measurements of the radius of curvature of polonium alpha-particles in the magnetic field of the annular magnet and the current through the small coil, together with Brigg's value[10] for the $H\rho$ of RaC′ alpha-particles, and Lewis and Bowden's value[11] for the ratio of the velocities of RaC′ alpha-particles and polonium alpha-particles. These values determine the velocity of the polonium alphas with a precision of 1 part in 5000.

The incident deuteron energy was determined from energy measurements of deuterons elastically scattered by carbon and oxygen nuclei in thin Formvar films.

After exposure the nuclear-track plates were processed and examined under microscopes, and the track-density distribution as a function of the radius of curvature was determined. For this purpose, it was necessary to correlate the positions of the nuclear-track plates during exposure with the position of the target. This correlation was made possible by means of a narrow slit which was located permanently with respect to the target position and which could be optically imaged on each plate during exposure. Since for each plate the range of radii covered is small and constant, the actual calculations involve in a sensitive way only the distance between the calibrating polonium source and the position of the beam on the target.

The track-density distribution functions were corrected for background-track density in those cases where it was necessary. This background-track density was determined from the leading edge of the distribution function at points sufficiently removed from the peak itself so that the contribution from the reaction concerned was negligible.

Because the photographic plates record particles that are emitted from the target within a small range of angles around 90 degrees with respect to the beam (±0.2 degree), the peaks obtained from measurements made across the full width of the plates are slightly broadened. A similar effect occurs because the particles are emitted from a line rather than a point source on the target. These small effects were corrected for analytically for each of the observed peaks.

Most of the targets used in this work consisted of thin surface layers of tantalum nitride on tantalum. Tantalum was selected because of its availability and the stability of its nitride. These targets were prepared in the following way. Ammonium nitrate was treated with an aqueous solution of sodium hydroxide, and the ammonia released was passed through barium oxide (a basic drying agent) and collected in a small evacuated quartz vessel containing small squares of sheet tantalum. The tantalum was then maintained at a temperature of approximately 1000°C for several minutes through the use of an induction heater. This procedure resulted in the formation of thin surface layers of tantalum nitride on the pieces of tantalum.

In addition to nitrogen, there was the possibility of the presence of other elements in the targets. The simplest and most effective means of identifying the nitrogen groups was by the variation of peak heights with targets of different isotopic concentrations. For this purpose, ammonium nitrate with the NH_3 radical enriched in N^{15} was obtained from the Eastman Kodak Company and was used in the preparation of enriched tantalum-nitride targets. A further check on the iden-

[9] Buechner, Strait, Stergiopoulos, and Sperduto, Phys. Rev. **74**, 1569 (1948).
[10] G. H. Briggs, Proc. Roy. Soc. **157A**, 183 (1936).
[11] W. B. Lewis and B. V. Bowden, Proc. Roy. Soc. **145A**, 250 (1934).

tification of certain groups was obtained by comparisons of the changes in energy of the groups with the changes in energy of the incident deuterons.

The presence of surface contaminants on the targets could lead to appreciable errors in the calculated values of reaction energies. In the present work a tantalum-nitride target essentially free of volatile contaminants was obtained by the use of a flat, mica-insulated heating element wound with 5-mil wolfram wire. The heating element was placed between the target and a metallic backing which was supported by a 40-mil wolfram wire. This target was maintained at a temperature corresponding to a dull red color during exposures. Since hot tantalum combines readily with both nitrogen and oxygen and in general absorbs gases, there was a strong possibility that nonvolatile surface contaminants remained even at high temperatures. The existence of such contaminants was determined from a comparison of the energies of one of the alpha-particle groups from the $N^{14}(d,\alpha)C^{12}$ reaction from a heated tantalum-nitride target and from a freshly prepared target consisting of a thin layer of ammonium nitrate deposited on a platinum backing. It was found that a small amount of such contamination was indeed present, and all of the measured Q-values obtained with the heated tantalum-nitride targets were corrected accordingly.

In order to investigate the proton groups having values of $H\rho$ less than those for the elastically scattered deuterons, it was necessary to discriminate between the two types of particles in the detection process. Since the solid-target yield of elastically scattered deuterons was much greater than the yield of reaction protons, it was not possible to make this discrimination by track-length comparisons under a microscope. Instead, the nuclear-track plates were shielded with aluminum foils of sufficient thickness to absorb the deuterons but not the protons. In this way, only the protons were allowed to register on the plates.

The Q-equation ordinarily used in the calculation of reaction energies has been derived on the basis of the non-relativistic relation between energy and momentum and errors comparable to the experimental errors would have been introduced by its use. Consequently, a relativistically correct Q-equation was derived and used in the calculation of the reaction energies.

III. EXPERIMENTAL RESULTS

As the analyzing magnet is employed in these experiments, each photographic plate is exposed at a fixed field strength and, hence, records an interval in the momentum spectrum of the particles emitted from the target. In Figs. 1 and 2 are plotted the results obtained from a number of plates exposed at various magnetic fields so as to cover the region of proton energy from 1.5 to 9.5 Mev. The field strengths for each plate were adjusted so that the regions covered by each overlapped slightly. The data shown in the figures were taken with an incident deuteron energy of 1.420 Mev and an unheated tantalum-nitride target. Only the observed proton groups are shown. In addition, a number of alpha-particle groups were observed, most of which corresponded to reactions in which C^{12} and C^{13} were formed as residual nuclei. For the reasons mentioned in the preceding section, those plates exposed at field strengths less than those corresponding to an $H\rho$ of 240 kgauss-cm were shielded with thin aluminum foils so as to prevent the recording of deuterons elastically scattered from the targets.

Of the proton groups observed, seven, numbered from 0 through 6 in the figures, were identified as arising from the $N^{14}(d,p)N^{15}$ reaction. Of the other peaks, four are due to the well-known groups from carbon and oxygen, and complete data for these peaks have not been plotted. The group at $H\rho=371$ kgauss-cm was identified by an independent measurement on an enriched C^{13} target as arising from the small concentration of C^{13} in the carbon contamination on the target. That the remaining groups were probably due to silicon was indicated by measurements on the shift in position of these groups as a function of the energy of the incident deuteron beam. That this assignment was correct was checked by a series of measurements on a thin silicon target. The presence of silicon contamination on the target is probably due to the fact that a quartz tube was used in the preparation of the tantalum-nitride layers.

As can be seen, the groups due to C^{12} and O^{16} are of very considerable intensity. The possibility that other proton groups due to nitrogen might be obscured by the presence of these intense groups was to a large extent eliminated by observations in these regions made with a heated target. Group 3 in Fig. 2 is plotted from data taken in this way, and its intensity relative to the other groups has been adjusted from measurements taken with the heated and unheated targets.

From the figures, it can be seen that the groups from nitrogen show a considerable tail on the low energy side. This is presumably due to the difficulty of preparing nitrogen targets. In the present case it is probable that

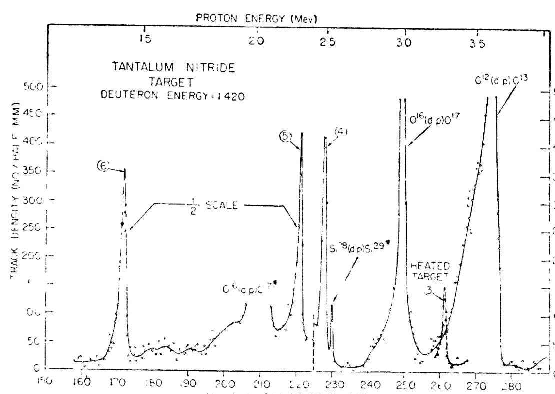

FIG. 2. Proton groups with energies between 1.2 and 4.0 Mev from tantalum-nitride target bombarded by deuterons.

TABLE I. Q-values for $N^{14}(d,p)N^{15}$.

Present work: Q-value in Mev	Present work: Level in N^{15} in Mev	Kinsey *et al.*[a] Level in N^{15} in Mev
8.615±0.010	0	0
3.339±0.005	5.276±0.006	5.287±0.010
3.310±0.005	5.305±0.006	
2.287±0.005	6.328±0.006	6.318±0.010
1.451±0.005	7.164±0.006	7.164±0.010
1.306±0.005	7.309±0.006	7.356±0.012
0.300±0.005	8.315±0.006	8.278±0.016

[a] See reference 3.

there is considerable diffusion of the nitrogen into the tantalum supports.

The measured half-widths of the proton groups were compared with the half-widths which would be expected if the broadening were due entirely to target thickness and to geometrical factors, such as the width of the entrance slit to the analyzing magnet. As can be seen from the figure, the peaks tend to broaden at the lower energies, as would be expected from the first of these factors. The only serious discrepancy in the measured and computed values occurred for the group corresponding to the 8.3-Mev level. The half-width of this group was considerably larger than the expected value, and it is possible that it is actually composed of two groups with a separation of about 10 to 20 kev.

Particular attention was paid to the particles having an $H\rho$ in the region of 300 kgauss-cm (groups 1 and 2). The track distribution in this region was accurately reproducible and varied with target thickness in the manner to be expected if the distribution were due to two closely spaced groups. These groups are of particular interest because they indicate the presence of two energy levels in N^{15} with the unusually small separation[12] of 29 kev.

The Q-values for the groups assigned to the $N^{14}(d,p)N^{15}$ reaction are listed in Table I.

In each case the values have been corrected for the effects of a surface layer of contamination, the thickness of which was estimated from the results of measurements carried out as outlined in the preceding section. In no case did these corrections amount to more than 4 kev. Also listed in Table I are the levels in N^{15} corresponding to these groups. These are compared in the table with the results of Kinsey, Bartholomew, and Walker which were obtained from measurements of the gamma-rays from the $N^{14}(n,\gamma)N^{15}$ reaction. The two sets of values for the energy levels agree in most cases within the probable errors, and in all cases within the limits of error; that is, three times the probable error.

An energy-level diagram for N^{15} showing the levels found in the present work is included in Fig. 1.

Kinsey and his collaborators[3] have also measured the Q-value for the $N^{14}(n,\gamma)N^{15}$ reaction. If the binding energy of the deuteron is subtracted from this value, 8.593±0.014 Mev is obtained for the Q of the $N^{14}(d,p)N^{15}$ reaction. This value is in fair agreement with the figure of 8.615±0.010 Mev obtained in the present work. It is to be noted that, in the present work, possible errors due to calibration, surface contaminants, and so forth tend to affect the energies of the group in the same direction so that the values obtained for the energy levels are somewhat more reliable than the Q-values for the individual groups.

Since N^{15} is present only to the extent of about 0.4 percent in ordinary nitrogen compounds, it is unlikely that groups from this isotope would be observed from unenriched nitrogen targets. In connection with the identification of the groups, however, targets with both normal and enriched concentrations of N^{15} were used in the investigation of the energy region covered in these experiments. Only one proton group was found that could be attributed to the $N^{15}(d,p)N^{16}$ reaction. For this group, a Q-value of -0.034 ± 0.005 Mev was obtained. While no higher energy group from this reaction was found at the bombarding energy used in these experiments, it is probable that the one observed does not correspond to the ground-state transition but is associated with the formation of N^{16} in the excited state at about 0.3 Mev indicated in the work of Wyly.[2]

We are indebted to the staff of the High Voltage Laboratory for much helpful discussion and assistance. We are particularly grateful to Miss C. O'Brien and Mr. W. A. Tripp for their careful measurements on the photographic plates.

[12] Possible interpretations regarding these levels have recently been discussed by D. Inglis, Phys. Rev. **78**, 616 (1950).