Both static and dynamic tests indicated that the field was being applied directly across the dielectric due to a positive charging of the secondary emission surface caused by the emission of secondary electrons and the high resistivity of the film.

The mechanism of the high yields has been suggested as an avalanche type of discharge due to liberation of electrons by high velocity electrons in the volume of the material near the surface.

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The $Al^{27}(d,p)Al^{28}$ and $Al^{27}(d,d')Al^{27}$ Reactions*

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A large heavy-particle magnetic spectrometer was used to study the proton and deuteron groups from the deuteron bombardment of a thin aluminum foil. Charged particles emitted at 90 degrees with respect to the the incident deuteron beam were analyzed by momentum in an annular-shaped magnetic field. Groups of protons and deuterons correspond to excited states in Al^{28} and Al^{27}, respectively. Fifteen groups of protons from the reaction $Al^{27}(d,p)Al^{28}$ were observed. Their Q values were 5.53, 4.49, 3.95, 3.36, 3.01, 2.06, 1.55, 0.70, 0.37, −0.27, −0.60, −0.84, −1.37, −1.86, and −2.98 Mev. The elastically scattered deuterons and five groups of inelastically scattered deuterons were also observed. Their Q values were 0, −0.97, −2.39, −3.17, −4.74, and −5.76 Mev.

I. INTRODUCTION

McMILLAN and Lawrence[1] first discovered that the protons from the deuteron bombardment of aluminum consisted of several groups. Since then this reaction has been studied by several observers[2–4] In this experiment 10-Mev deuterons bombarded an aluminum target in a magnetic spectrometer capable of focusing 15-Mev protons on a nuclear research emulsion, which was used as a particle detector. A search was made for proton groups corresponding to excited states in Al^{28} up to 9 Mev above the ground state.

The inelastic scattering of deuterons was first reported by Greenless, Kempton, and Rhoderick[5] in 1949. They observed two groups of deuterons inelastically scattered by aluminum. Holt and Young[6] subsequently observed these two deuteron groups and gave Q values (Q values and energy levels have the same magnitude for inelastic scattering but opposite signs) of -0.99 ± 0.05 and -2.17 ± 0.05 Mev. In the present experiment, the scattered deuterons were recorded simultaneously with the protons in the nuclear emulsions.

II. APPARATUS

A large charged-particle spectrometer, having 180° magnetic focusing, was made, using an annular magnet similar to one described by Cockroft.[7] The mean radius of the annulus is 42 cm, the width of the annulus is 8 cm, and the width of the gap between the pole faces is 0.658 cm. A collimated beam of deuterons from the Washington University cyclotron passes through a small hole in the magnet pole face and strikes a 0.2-mil aluminum target in the gap between the pole faces. The particles from a nuclear reaction which leave the target at 90° with respect to the incident beam travel in the evacuated gap between the pole faces of the annular magnet. The magnetic field in the gap can be adjusted from nearly zero to about 16,000 gauss. With a given magnetic field, all of the particles in a certain momentum interval will stay in the annulus through 180° and strike a nuclear photographic plate inclined in the magnet gap. The angle of inclination of the nuclear plate is 12° with respect to the pole faces. The plate is attached to a holder equipped with a long rod which is used to insert the plate between the pole faces of the magnet. This rod enables the plate holder to be placed in an air lock, which is then evacuated. The valve to the main vacuum system is opened and the plate is pushed into position between the pole faces.

The magnetic field of the annular magnet is produced by a current of up to two amperes in a water-cooled coil situated between the magnet core and the pole faces. The constant magnet current is supplied by a grid-controlled thyratron rectifier.

The magnetic field was measured with a Leeds and Northrup ballistic galvanometer in series with a flip coil which is located in the half of the annulus through

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* Assisted by the joint program of the ONR and AEC.

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which particles do not pass. Polonium alpha-particles, which have a $B\rho$ of[8] 3.3159×10^5 gauss-cm, were used to calibrate the galvanometer deflection against the magnetic field.

In order to regulate the bombardment time, an insulated faraday cup behind the target collects the deuteron beam and allows this charge to produce a potential across a condenser. This potential is measured by an electrometer so that the desired bombardment can be obtained.

III. EXPERIMENTAL PROCEDURE

A series of Ilford C2 nuclear research plates, having an emulsion thickness of 50 microns, was exposed in the spectrometer such that the momentum, or $B\rho$, values of adjacent plates were overlapped by about one-third. In this way, each particle group was found on more than one plate. After the plates were developed, they were scanned with a microscope by counting the tracks within transverse swaths one mm apart along the plate. Protons can easily be distinguished from deuterons because if they have the same momentum and come to focus near each other on the photographic plate, the protons will have approximately twice the energy of the deuterons and hence much longer ranges in the emulsion.

Before a number-of-tracks-*versus*-$B\rho$ curve can be made, the data from the microscope must be corrected to account for the facts that different parts of the nuclear plate subtend different solid angles with respect to the target, and that the $B\rho$ intervals of the microscope swaths of different plates are not the same. After these corrections were applied, the data were overlapped so that fairly smooth curves could be drawn through the points. It was estimated that, due to the energy loss in the aluminum target, the true or ideal peak position corresponded very closely in $B\rho$ with a point one-third of the height of the high $B\rho$ side of the actual peaks, as suggested by Buechner.[9] The momentum of the charged-particle groups was determined from the measurements of their radii of curvature in the magnetic field and the magnetic field strength. The groups' energies were calculated from their momenta. Knowing the kind of particles in a group and their energy enabled the Q values of the reaction to be computed using the well known formula derived from the laws of conservation of energy and momentum in nuclear reactions. Finally, the energy levels of a nucleus were obtained by subtracting the Q-values of the various particle groups produced in the nuclear reaction with the nucleus from the Q-value of the highest energy or ground-state particle group.

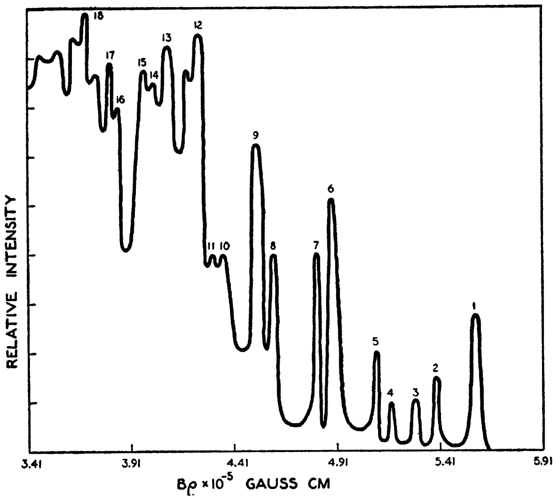

FIG. 1. $Al^{27}(d,p)Al^{28}$ proton spectrum. Peaks 14, 16, and 17 may be due to protons from the reaction $C^{12}(d,p)C^{13}$.

IV. RESULTS

The results of the survey of the $Al^{27}(d,p)Al^{28}$ reaction are shown in Fig. 1. Fifteen proton peaks can be assigned to Al^{27} (the only naturally occurring aluminum isotope). It is not possible from this experiment to say if peaks 14, 16, and 17 are due to aluminum or not. It is possible that these peaks may correspond to excited states of C^{13} formed in the $C^{12}(d,p)C^{13}$ reaction, since they occur where such peaks are to be expected. Although clean aluminum targets were used, a carbon deposit may build up on the aluminum foil during the combardment. The carbon may come from the oil used in the diffusion pump, or it may come from organic molecules given off by the hot magnet coil which was impregnated with Glyptal. Separate experiments show that peaks due to such a carbon deposit do occur. The ground-state proton group from the $C^{12}(d,p)C^{13}$ reaction is sufficiently close to the seventh group that their errors slightly overlap. It seems safe to assign the seventh proton group to aluminum, as it has been reported by several ob-

TABLE I. Proton groups observed from a thin aluminum target bombarded with 10.4-Mev deuterons.

Proton group	$B\rho\times10^{-5}$ gauss cm	Group energy in Mev	Q-value in Mev	Energy level in Mev
1	5.57	14.68	5.53	0
2	5.37	13.68	4.49	1.04
3	5.27	13.16	3.95	1.58
4	5.16	12.59	3.36	2.17
5	5.08	12.25	3.01	2.52
6	4.89	11.33	2.06	3.47
7	4.79	10.84	1.55	3.98
8	4.60	10.02	0.70	4.83
9	4.52	9.70	0.37	5.16
10	4.37	9.08	−0.27	5.80
11	4.29	8.76	−0.60	6.10
12	4.23	8.53	−0.84	6.40
13	4.10	8.02	−1.37	6.90
15	3.98	7.55	−1.86	7.40
16	3.68	6.46	−2.98	8.50

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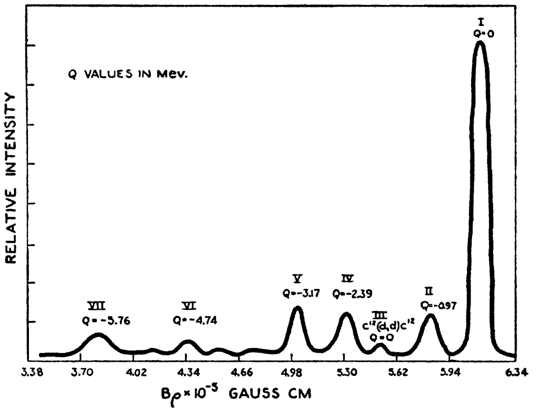

FIG. 2. Spectrum of deuterons scattered by Al^{27} observed by magnetic analysis. Peak III is due to elastically scattered deuterons from C^{12}.

servers. However, since the energy level in Al^{28} corresponding to this proton group has only been observed through the (d,p) reaction, it is not absolutely certain that the seventh proton group is from aluminum. There are indications of proton peaks near peak 18 on each side, and a peak between 12 and 13, but the statistics of the track counts make it impossible to be sure that they are real.

The resolution obtained for these proton groups is about one percent. The width of the peaks is due to several causes: (1) the deuteron beam is not monoenergetic but has a half-width of about 75 kev. (2) The target area is about 3 mm wide. (3) The particles lose energy in the aluminum target, the amount of loss depending on the depth in the target foil at which the (d,p) reaction occurs. (4) The focusing properties of the magnet contribute about one mm to the width of the peaks.

Table I gives the data concerning the proton groups and the energy levels in Al^{28}. The last two proton groups correspond to higher excited states than previously studied by the (d,p) reaction. The last proton group is from a virtual level in Al^{28} such that the residual nucleus may go to the ground state by the emission of a neutron.

The scattered deuteron groups are shown in Fig. 2. Peak I is elastically scattered deuterons, while peaks II, IV, V, VI, and VII are inelastically scattered deuterons from Al^{27}. The small peak III is just where elastically scattered deuterons from C^{12} are expected to be. The origin of the carbon on the aluminum has been previously mentioned. Table II gives the pertinent data concerning the groups of scattered deuterons. The errors here are estimated to be the same as for the proton peaks, 0.2 Mev.

TABLE II. Groups of deuterons scattered by Al^{27}. All but the first group are inelastically scattered deuterons corresponding to excited states in Al^{27}.

Peak	$B\rho$ in gauss cm	Group energy in Mev	Energy level in Mev
I	6.14×10^5	8.98	0
II	5.81×10^5	8.08	0.97
IV	5.32×10^5	6.76	2.39
V	5.02×10^5	6.02	3.17
VI	4.38×10^5	4.57	4.74
VII	3.89×10^5	3.62	5.76

The energy of the cyclotron deuteron beam was computed from the elastically scattered deuteron peak. The deuteron beam energy was found to be 10.42±0.2 Mev.

It is interesting to compare these levels in Al^{27} obtained by inelastic scattering of deuterons with levels observed by other reactions. Rhoderick[10] scattered 4.5-Mev protons from the Cambridge cyclotron with aluminum and used a proportional counter in conjunction with absorbing foils to detect the scattered protons. He found two levels, one at 0.97±0.02 Mev and another at 2.15±0.05 Mev, which are near the first two found in this experiment. Brolley, Sampson, and Mitchell[11] used much higher energy protons and a scattering chamber similar to Rhoderick's to study the inelastically scattered protons. They found levels at 0.95, 2.15, and 2.93 Mev in Al^{27}. These values correspond fairly well with the first three levels reported here. The level of this experiment at 4.74 Mev does not seem to correspond with a previously observed level. The highest energy level in Al^{27} found by studying the scattered deuterons correspond very well with one reported by Swann, Mandeville, and Whitehead.[12] They studied the $Mg^{26}(d,n)Al^{27}$ reaction and found an energy level at 5.81±0.07 Mev above the ground state. In general the nuclear energy levels in Al^{27} that were determined by inelastically scattered deuterons are within experimental errors of the values of levels determined by other reactions, which is as it should be, since the energy levels of a given nucleus should be independent of the method of excitation.

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