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Magnetic Analysis of the $Al^{27}(d,p)Al^{28}$ Reaction*

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Thin aluminum targets have been bombarded with 1.8-, 2.0-, and 2.1-Mev deuterons. Protons emerging at 90 degrees with respect to the deuteron beam have been analyzed in a magnetic spectrograph. Fifty proton groups have been assigned to the $Al^{27}(d,p)Al^{28}$ reaction, corresponding to the ground state and forty-nine excited states in Al^{28} between 0 and 6.35 Mev. Most of the levels form clusters, and spacings as low as 13 kev have been observed.

I. INTRODUCTION

SINCE the $Al^{27}(d,p)Al^{28}$ reaction was first observed in 1934 by Lawrence and Livingston,[1] it has been studied by a number of workers[2–11] in order to determine the positions of the energy levels in Al^{28} and the angular distribution of the protons in the various groups. A total number of fifteen proton groups assigned to Al^{28} levels has been reported.

Around 8-Mev excitation energy, the Al^{28} level structure has been investigated by Henkel and Barschall[12] by measurements of the neutron cross section in Al^{27}. The level density they find seems to be unusually high when comparison is made with neighboring nuclei at the same or higher excitation energies. It may therefore seem reasonable to expect a comparatively high level density at lower excitation energies in Al^{28} as well.

In this paper are reported the results of measurements on the $Al^{27}(d,p)Al^{28}$ reaction made with a 180-degree magnetic spectrograph. The Q value of the ground state and the existence of a 31-kev level have been previously reported.[13,14] This low-lying level has recently also been observed by Smith and Anderson,[15] who have found a 31.4-kev gamma-ray from aluminum targets bombarded with deuterons. Forty-eight more proton groups have now been assigned to energy levels in Al^{28} up to an excitation energy of 6.35 Mev. This large number of levels could not have been observed by previous workers for reasons of resolution.

The gamma-rays from the $Al^{27}(n,\gamma)Al^{28}$ reaction have been studied by Kinsey *et al.*,[16] using a pair spectrometer. Twenty-nine of the gamma-energies observed, taken in conjunction with the results of the present work, may be assigned to transitions from the capture state to an excited state or from an excited state to the ground state.

II. EXPERIMENTAL ARRANGEMENT

The apparatus and experimental techniques were essentially the same as those that have been described in previous papers.[17,18] Deuterons accelerated in the

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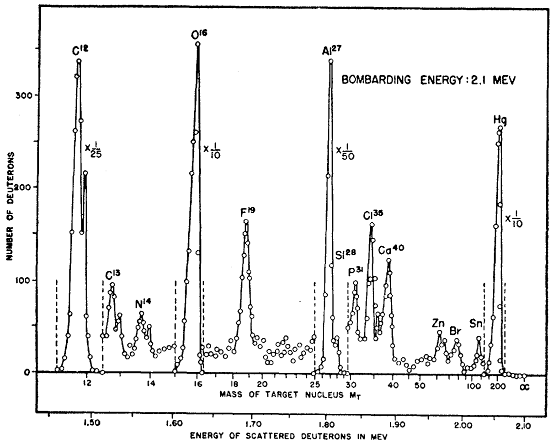

FIG. 1. Mass spectrum of aluminum-on-Formvar target obtained by observing elastically scattered deuterons.

field of an electrostatic generator were focused and deflected 90 degrees through a magnetic analyzer. After passing through a defining slit, the horizontal beam hit the target which was placed between the annular-shaped pole pieces of the magnetic spectrograph. Charged particles leaving the target at 90 degrees with respect to the incident beam were analyzed in the 180-degree, single-focusing spectrograph. Eastman Kodak NTA nuclear-track plates were used for recording the charged particles. Discrimination between protons, deuterons, and alpha-particles was made on the basis of differences in track lengths. Only results from the (d,p) and (d,d) reactions are presented in this paper, the $Al^{27}(d,\alpha)Mg^{25}$ reaction being reported elsewhere.[19] The tracks were counted under a microscope in strips of 0.23 or 0.50 millimeter in width, and the number of tracks in each strip was plotted *versus* strip distance from the target or *versus* $H\rho$.

Because of the complexity of the Al^{28} spectrum, it was necessary to improve the resolution of the apparatus for the present work. This was accomplished partly by reducing the width of the exposed strip of the target to 0.3 mm and partly by reducing the solid angle of the charged-particle bundle admitted through the spectrograph.

Experience has shown that the surface contamination collected on a target during exposures is of uneven thickness so that it affects the energy spread, or width, of the observed peaks of charged particles as well as their position in the $H\rho$ diagram. To minimize this effect, a liquid-air trap was mounted in the vacuum line between the 90-degree analyzer and the spectrograph. This trap collected most of the bothersome vapors that presumably originated in rubber gaskets and stopcock grease.

The excitation current for the spectrograph magnet was stabilized to about 1 part in 15,000 and the current for the 90-degree analyzer, to about 1 part in 5000.

The resolution obtained was $(H\rho)/\Delta(H\rho)\approx 1500$ at the upper end of the observed proton spectrum (390 kilogauss-centimeters) and 250 at the lower end (150 kilogauss-centimeters).

As in previous experiments in this laboratory, polonium alpha-particles were used to calibrate the fluxmeter of the annular magnet. For this purpose, the target was replaced by a silver wire coated with polonium. The value of $H\rho$ for polonium alpha-particles used as an absolute standard was 3.3159×10^5 gauss-centimeters (absolute emu), accurate to 1 part in 5000.

The incident energy of the deuterons was calculated from the observed energy of deuterons elastically scattered from the C^{12} nuclei in a thin Formvar target.

The aluminum targets employed in these experiments were prepared by evaporating aluminum onto Formvar films supported by nickel-wire frames. The 2- to 5-kev thick aluminum targets were found capable of withstanding a 1-microampere beam indefinitely, whereas a Formvar backing alone would break when exposed to more than 0.1 microampere.

III. MASS ANALYSIS OF THE TARGET

In addition to aluminum, the targets with backing and surface contamination contained several other elements, which all had to be considered as possible contributors to the yield of protons from (d,p) reactions. For the correct assignment of the different peaks observed, it was therefore highly desirable to know what elements were present and their relative abundance. In the present case, a quantitative analysis of the target material was most easily performed by aid of the energy spectrum of deuterons elastically scattered from the target.

Figure 1 shows the number of deuteron tracks as a function of the energy of the scattered deuterons. These

TABLE I. Mass analysis of aluminum target on Formvar backing.

Element	Element number Z	Significant isotope M	No. tracks in peak divided by Z^2	Origin
C	6	12, 13	620	Backing and vacuum system
N	7	14	1.9	Vacuum system
O	8	16	103	Backing, Al_2O_3, vacuum system
F	9	19	3.5	Vacuum system?
Al	13	27	100	Evaporated material
Si	14	28	7.2	Vacuum system
P	15	31	0.53	Backing and/or vacuum system
Cl	17	35, 37	0.97	Backing and/or vacuum system
Ca	20	40	0.43	Backing and/or vacuum system
Zn	30	66	0.09	Evaporator
Br	35	81	0.08	Vacuum system
Sn	50	120	0.02	?
Hg	80	202	0.47	Vacuum system

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

[19] Endt, Enge, Haffner, and Buechner, Phys. Rev. 87, 27 (1952).

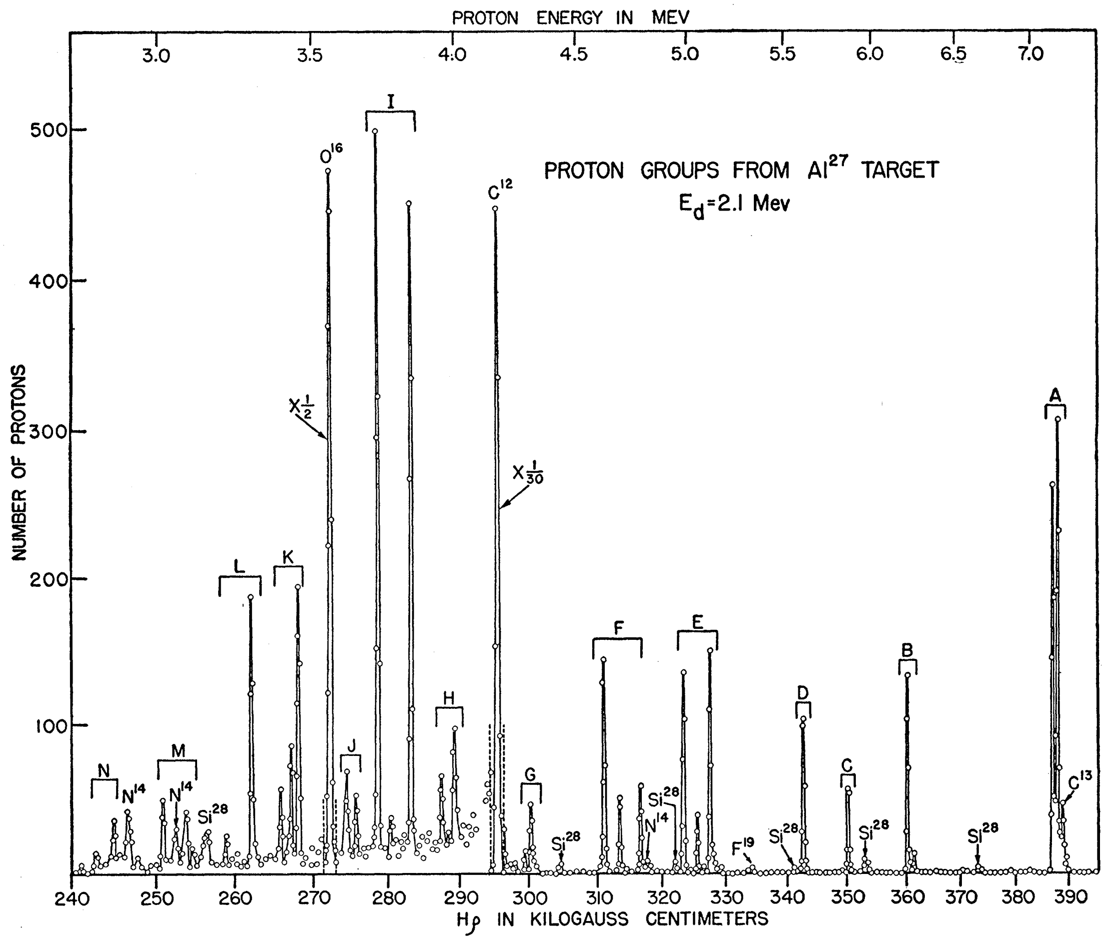

FIG. 2. Protons from an aluminum-on-Formvar target bombarded with 2.1-Mev deuterons.

deuterons were recorded simultaneously with the protons from the (d,p) reactions that took place in the same target. The bombarding energy was 2.1 Mev.

The observed output energy E_{out} is related to the mass of the target nucleus M_T through the equation

$$E_{\text{out}}=\frac{M_T-M_D}{M_T+M_D}E_{\text{in}}, \quad (1)$$

where M_D is the mass of the deuteron and E_{in} is the bombarding energy. The equation holds for scattering through 90 degrees, the relativistic correction being negligible for the present purpose.

The different peaks of deuterons shown in Fig. 1 have been assigned to different target nuclei according to Eq. (1). Both the energy and mass scales refer to the point of one-third maximum on the right side of a peak.[20] For the elements in the upper region where the resolution is poor, the mass of the heaviest isotope of appreciable abundance has been entered into Eq. (1). Peaks resulting from elements in the backing are displaced slightly to the left of their proper position in the diagram because of the energy loss of the deuterons which penetrated the aluminum layer twice. Peaks resulting from elements distributed through, or on both sides of, the target are broader than the others for the same reason (e.g., N^{14}).

No deuteron peaks were observed above the background in the energy region 0.92 to 1.45 Mev, corresponding to mass numbers 6 through 11. A detectable peak of inelastically scattered deuterons corresponding to the 0.837-Mev level[21] in Al^{27} thus also failed to appear.

Table I gives a list of elements which, according to Fig. 1, have been present in the target. An estimate of relative abundance of the various elements has been obtained by assuming Rutherford scattering. Therefore, the number of tracks in each peak has been divided by the square of the appropriate element number. The resulting figures are given, relative to that for aluminum, in column 4. In column 5, the different elements

[20] The energy scale in Fig. 1 is logarithmic. The mass scale therefore follows the equation $x_\infty - x = k\tanh^{-1}(M_D/M_T)$ and is nearly linear in M_D/M_T as long as this quantity is small.

[21] D. M. Van Patter and W. W. Buechner, Phys. Rev. **87**, 54 (1952).

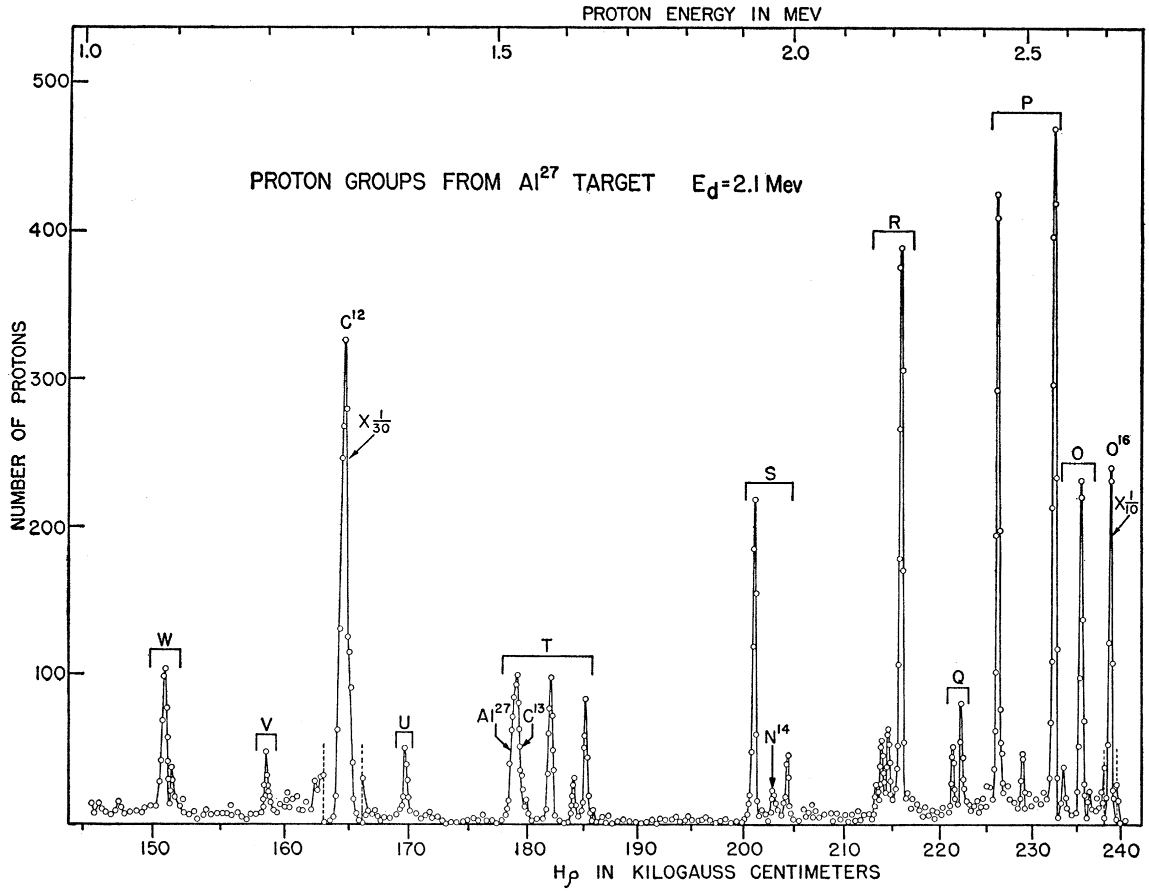

FIG. 3. Protons from an aluminum-on-Formvar target bombarded with 2.1-Mev deuterons.

have been tentatively assigned to backing, evaporated material, or surface contamination resulting from gaskets in the vacuum system. A further investigation as to the origin of the different contaminants is outside the scope of this paper.

IV. ASSIGNMENT OF THE PROTON PEAKS

Figures 2 and 3 give $H\rho$ diagrams of protons from an aluminum target bombarded with 2.1-Mev deuterons. Each exposure on one nuclear track plate covered about 5 percent in $H\rho(\Delta\rho/\rho=0.05)$, so that the whole region of $H\rho$ shown in Figs. 2 and 3 is made up of data from twenty-three exposures at different values of the field strength. The proton peaks that have been assigned to the $Al^{27}(d,p)Al^{28}$ reaction are designated in the figures by capital letters. In many cases, each letter refers to several closely spaced groups. This rather arbitrary division of the groups was chosen for convenience in reference, since, as the work progressed and the performance of the apparatus improved, additional weak peaks were found close to the previously discovered intense groups.

Several surveys were made at 1.5-, 1.8-, 2.0-, and 2.1-Mev bombarding energies.[22] The experimental improvements mentioned above were made while these surveys were in progress. All the proton peaks assigned to the $Al^{27}(d,p)Al^{28}$ reaction appeared in each of the three most recent surveys.

The double structure of the group labeled W in Fig. 3 was observed only in the last survey at maximum resolution. A slight possibility exists that the effect might be due to a double exposure; that is, the magnet current might have been out of control without this having been observed. Further work is required to clear up this point, and group W has been treated as corresponding to one level in the following. There are also some indications of weak structure between the three peaks in group E and between the two peaks in group B. These details will be further investigated with a new magnetic spectrograph which is now under construction.

The mass analysis of the target showed that a number of elements other than aluminum had to be considered as possible contributors to the yield of protons. It should be remembered, however, that at the

[22] The first survey, at 1.5 Mev, was made by K. Huang, B. Sc. thesis, Massachusetts Institute of Technology (May, 1950), unpublished. Because a fairly thick target was used, only fifteen levels in Al^{28} were reported.

bombarding energies used the cross sections for (d,p) reactions decrease very rapidly with increasing atomic number. Moreover, according to Table I, the abundance of the higher elements was very low. In addition to Al^{27}, the nuclei that could be expected to give detectable contributions were therefore C^{12}, C^{13}, N^{14}, O^{16}, F^{19}, and Si^{28}. Proton peaks caused by all of these target nuclei were actually found, and they are labeled accordingly in Figs. 2 and 3.

The sorting out of the peaks was greatly facilitated by the fact that parallel work on other target materials was in progress at this Laboratory. Comparison was made with work on nitrogen, fluorine, sodium, silicon, and phosphorus targets. The strong peaks from carbon and oxygen always appeared and are well known from previous work.[18,23] One of the peaks from the $C^{13}(d,p)C^{14}$ reaction coincided at 2.1-Mev bombarding energy with an aluminum peak in group T, Fig. 3. At other bombarding energies, two separate peaks appeared. Deuterium, nitrogen, and silicon also seem to have been present in all targets, presumably as surface contamination. At the position where the strongest peak from F^{19} could be expected to appear, a few tracks were found as shown in Fig. 2 at $H\rho = 334$ kilogauss-centimeters.

The proton peaks from (d,p) reactions on Si^{29}, Si^{30}, and P^{31} were not detected in the work on aluminum targets. Protons from the $D^2(d,p)T^3$ reaction have at 2.1-Mev bombarding energy approximately the same energy as those from O^{16}. These protons appear at $H\rho = 272$ kilogauss-centimeters.

TABLE II. $Al^{27}(d,p)Al^{28}$ Q values and energy levels in Al^{28}.

Group	Rel int	Q value Mev	Excitation energy Mev	Group	Rel int	Q value Mev	Excitation energy Mev
A_1	100	5.494	0	L_2	5.4	1.379	4.115
A_2	69	5.463	0.031	M_1	19	1.256	4.238
B_2	4.6	4.520	0.974	M_2	13	1.187	4.307
B_1	38	4.479	1.015	N_1	11	1.037	4.457
C	16	4.127	1.367	N_2	11	0.982	4.512
D	35	3.869	1.625	O_1	130	0.808	4.686
E_1	45	3.357	2.137	O_2	17	0.760	4.734
E_3	13	3.296	2.198	P_1	222	0.735	4.759
E_2	40	3.226	2.268	P_3	14	0.657	4.837
F_2	19	3.010	2.484	P_2	170	0.596	4.898
F_3	16	2.916	2.578	Q_1	30	0.506	4.988
F_1	49	2.842	2.652	Q_2	16	0.487	5.007
G_1	18	2.514	2.980	R_1	180	0.366	5.128
G_2	4.6	2.488	3.006	R_2	31	0.338	5.156
H_1	32	2.203	3.291	R_3	26	0.325	5.169
H_2	15	2.152	3.342	R_4	11	0.312	5.182
I_2	121	2.036	3.458	S_2	19	0.122	5.372
I_3	12	1.962	3.532	S_1	92	0.059	5.435
I_1	158	1.907	3.587	T_2	42	−0.241	5.735
J_2	11	1.829	3.665	T_4	13	−0.261	5.755
J_1	15	1.799	3.695	T_1	56	−0.298	5.792
K_1	71	1.621	3.873	T_3	35	−0.361	5.855
K_2	32	1.594	3.900	U	19	−0.517	6.011
K_3	18	1.562	3.932	V	44	−0.696	6.190
L_1	58	1.463	4.031	W	84	−0.813	6.307

[23] Sperduto, Holland, Van Patter, and Buechner, Phys. Rev. **80**, 769 (1950).

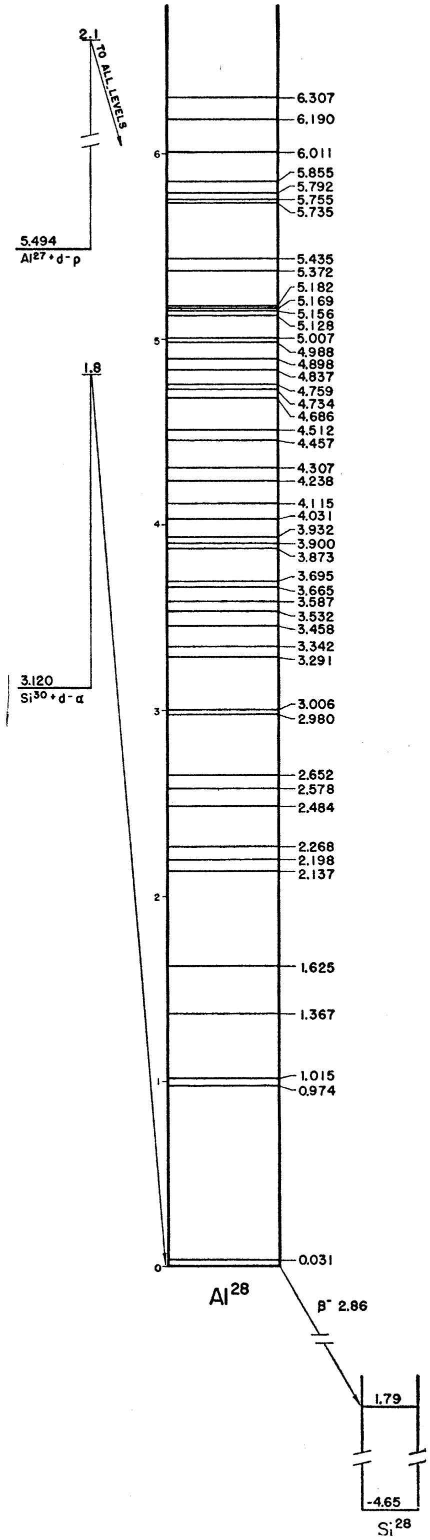

FIG. 4. Energy-level diagram for Al^{28}.

Through the comparison with work on other targets, all proton peaks resulting from contamination nuclei with mass number $A<35$ were sorted out. Partly in order to rule out the possibility that nuclei of greater

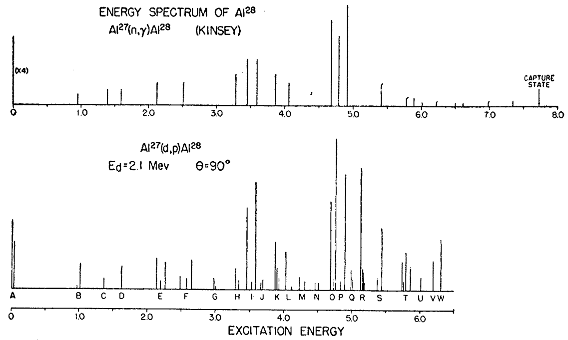

FIG. 5. Energy-level diagrams for Al^{28} with relative intensities.

mass number might have been responsible for any of the observed groups, the shift of proton energy associated with a change in bombarding energy was determined for each peak. Through a relationship similar to that expressed in Eq. (1), it was possible to determine the mass of the target nucleus responsible to within about 5 mass units.[24] These measurements also indicated that the assignments of the fifty proton peaks to the $Al^{27}(d,p)Al^{28}$ reaction were correct. It is felt that the comparison with work on other targets and the energy-shift measurements together provided unambiguous assignments to the observed groups.

V. ENERGY LEVELS IN Al^{28}

Q values corresponding to the fifty proton peaks assigned to the $Al^{27}(d,p)Al^{28}$ reaction have been calculated from experimental data obtained at two or more bombarding energies. Of the individual Q values, averages have been formed for each peak. The maximum deviation of any individual result from these averages was 4 kev for any peak in Fig. 2 and 2 kev for any peak in Fig. 3.

The average Q values are presented in Table II, which also gives the excitation energies of the corresponding levels in Al^{28}. The different levels are marked with the group letter and a subscript denoting a grading according to relative intensity as found under the present experimental conditions.

The probable errors associated with the Q values and excitation energies in Table II have not been evaluated for each level. As regards the Q values, the error for that of the ground state has previously been given as ± 10 kev ($Q = 5.494 \pm 0.010$ Mev[13]). The general trend is a decrease in error for decreasing Q values. The probable errors associated with the excitation energies increase from ± 7 kev for group B to ± 12 kev for the highest levels. Differences between excitation energies for levels in the same group are quite accurately known because the corresponding proton peaks as a rule appeared on the same nuclear-track plate. The directly measured differences have been conserved in the list of excitation energies in Table II. The close spacings between the levels R_2 and R_3 and between R_3 and R_4 have been most accurately measured, as 13.5 ± 1.0 kev and 12.5 ± 1.0 kev, respectively. The excitation energy of the first excited state has previously been given as 31.2 ± 2.0 kev.[13]

The relative intensities given in Table II apply to the number of protons emerging at 90 degrees with respect to the deuteron beam at a bombarding energy of 2.1 Mev.

A conventional energy-level diagram for Al^{28} is presented in Fig. 4. In Fig. 5, lower part, the diagram has a different orientation, and the relative intensities as given in Table II are represented by the height of the lines. The diagram in the upper part of Fig. 5 has been constructed from the (n,γ) results of Kinsey *et al.*[16] It is interesting to note that the maxima and minima in relative intensities have the same locations in the two diagrams.[25]

We are indebted to our colleagues in the High Voltage Laboratory who have collaborated in various stages of this work. We wish to thank all who have assisted in connection with the reading of photographic plates, especially Mrs. Cecilia Bryant, Mr. W. A. Tripp, and Miss Jane Pann.

[24] These measurements were performed with special care in the case of the 31-kev level (see reference 13).

[25] In Fig. 5, upper left, instead of (x 4), read (x 1/4).