$Si^{28}(d,\alpha)Al^{26}$ Reaction*

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Earlier work on the $Si^{28}(d,\alpha)Al^{26}$ reaction was extended and improved. The ground state Q-value of the reaction was remeasured and found to be 1.428±0.004 Mev. Levels were found with excitation energies of (in Mev) 0.229±0.003, 0.418±0.002, 1.060±0.002, 1.762±0.003, 1.853±0.003, 2.073±0.003, 2.368±0.003, 2.548±0.004, 2.663±0.004, 2.741±0.005, 2.916±0.006, 3.075±0.006, 3.160±0.006, 3.407±0.006, 3.510 ±0.010, and 3.596±0.010. Seven of these have not been reported previously. The yields of the reaction leading to the ground state, the first excited state, and the second excited state were measured as a function of bombarding energy in the range 5.5 Mev to 7.5 Mev. There is strong resonance structure. The angular distributions for the reaction leading to these three states were obtained at 7.03 Mev bombarding energy. At this energy the total yield of the isotopic-spin forbidden reaction leading to the first excited state is 10% of the yield to the ground state. This violation of the selection rule can be explained by Coulomb force effects. The second $T=1$ level could not be observed and the previous suggestion that the level at 3.16 Mev is the third $T=1$ level seems to be incorrect. A comparison of the data with the results of other experiments is made. Energy levels of Al^{27} seen in the $Si^{29}(d,\alpha)Al^{27}$ reaction are listed and compared with results from $Al^{27}(p,p')Al^{27*}$. A new level at 5.745±0.012 Mev was found plus several levels above the range of excitation previously covered.

I. INTRODUCTION

SIX Q-values for the $Si^{28}(d,\alpha)Al^{26}$ reaction leading to the ground state and five excited states were measured in a previous experiment[1] in which a 180-degree magnetic spectograph was used and observations were made only at 90 degrees. The mass of Al^{26} was determined, and the previous question regarding the isotopic-spin of the ground state was answered. Action of the isotopic-spin selection rule presumably limited the states observed to those with $T=0$.

Later experiments with gamma rays from proton bombardment of Mg^{25} showed the existence of a state at[2] 0.235±0.009 Mev or 0.219±0.013 Mev.[3] This is the expected position for the $T=1$ state of Al^{26} which corresponds to the ground state of Mg^{26}. A simultaneous measurement[4] of the neutrons from the $Al^{27}(\gamma,n)Al^{26}$ reaction and the positrons from the rapid decay of the first excited state supported the conclusion that the first excited state lies at about 200 kev and has $T=1$. It is this state that beta decays to Mg^{26} with the well-known 6.7-second half-life. Al^{26} in its ground state has been produced in measurable quantity and the decay half-life found to be of the order of 10^6 years.[5]

Another pertinent result is the accurate measurement of the Q-value for the $Mg^{26}(p,n)Al^{26*}$ reaction leading to the first excited state.[6] From this number and the H^1-n mass difference, the $Al^{26*(T=1)}-Mg^{26}$ energy difference may be calculated. Two other methods may be used to find this difference, one, a combination of the measured $Si^{28}(d,\alpha)Al^{26*}$ Q-value and the known $Si^{28}-Mg^{26}$ mass difference and the other an adjustment of the $Al^{25}-Mg^{25}$ mass difference based on the assumption of charge independence of nuclear forces. The results of these three calculations will be compared later.

Additional work on the $Mg^{25}(p,\gamma)Al^{26}$ reaction[7] showed the presence of eight new levels at excitation energies above those covered in the earlier $Si^{28}(d,\alpha)Al^{26}$ experiment. One of these, which was also reported in reference 3 and is discussed by Green *et al.*,[8] is probably the second $T=1$ level. These data will be compared with the present work later. Twenty-one levels between 6.6 and 7.5 Mev are known from resonances in the (p,γ) yield. A list of these levels is given by Endt and Braams.[9]

The present work was inspired by the observation of a violation of the isotopic-spin selection rule in the $O^{16}(d,\alpha)N^{14}$ reaction.[10] A similar violation in the $Si^{28}(d,\alpha)Al^{26}$ reaction leading to the first excited state was sought. A preliminary report of the discovery of this violation was made.[11] Many of the data were taken from the nuclear track plates exposed in the course of the $O^{16}(d,\alpha)N^{14}$ experiments.

This paper gives an improved value for the ground state Q-value, the excitation energies of sixteen excited states, the yield as a function of energy, and the angular distribution at one energy, of the ground state, first excited state, and second excited state groups.

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† Much of the track counting and data analysis was done at the author's present address, The University of Notre Dame, Notre Dame, Indiana.

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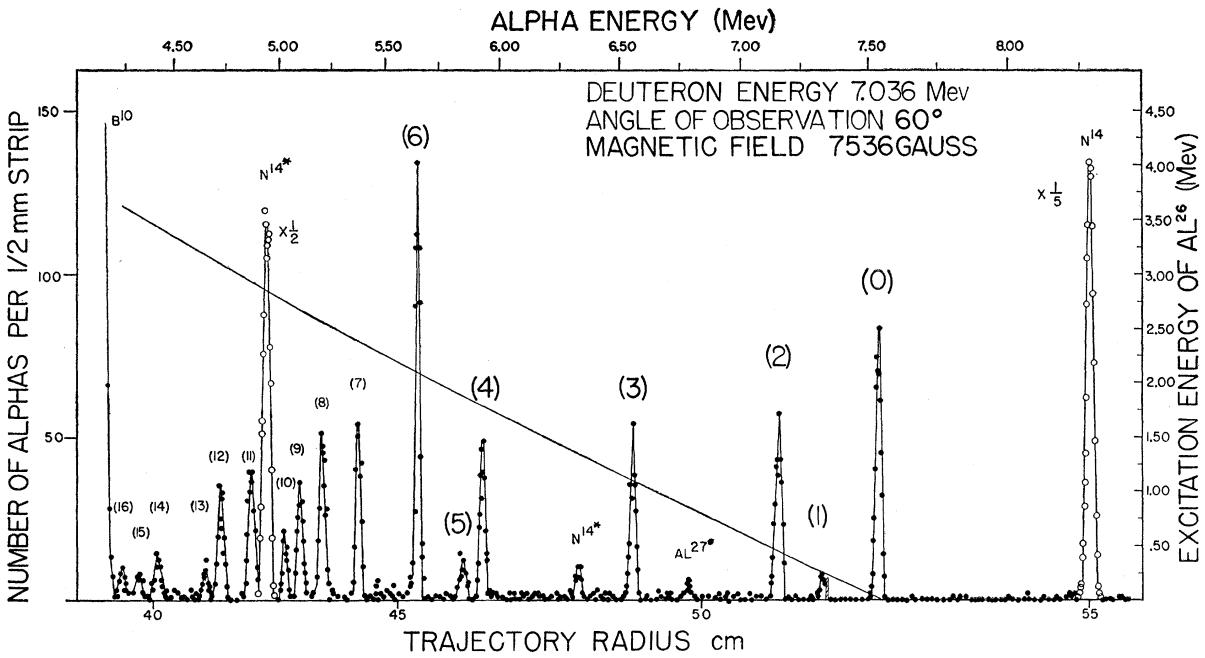

FIG. 1. Alpha particles from the deuteron bombardment of a SiO_2 on Formvar target. Groups leading to levels in Al^{26} are numbered. Other groups are labeled with the symbol of the residual nucleus. The intersection of the sloping line with a numbered group, read against the right-hand ordinate scale gives the Al^{26} excitation energy.

II. Q-VALUES AND ENERGY LEVELS

Deuterons from an electrostatic accelerator bombarded targets of SiO_2 evaporated onto thin Formvar backings. Reaction products from the targets were analyzed with the MIT broad-range spectrograph.[12] The procedure used to obtain the particle energy from the measured position of a group on the nuclear track plate is discussed in this reference.

For most of the runs the input energy was found by using the measured position of the proton group from the $O^{16}(d,p)O^{17}$ reaction, and the known ground state Q-value.[13] For the remainder of the runs, the input energy was found by measuring the energy of the deuteron groups elastically scattered from silicon and oxygen.

When the angle of observation was less than 70 degrees, the target was set in the transmission position and a correction for alpha-particle energy loss in the target was required. In the runs used to measure Q-values target thicknesses were low enough to give a negligible energy loss for the $O^{16}(d,p)O^{17}$ protons. The input energy calculated from the position of this group was used for the (d,α) reaction, so that no correction was needed for deuteron energy loss. The average energy loss in the target of alpha-particles from the $O^{16}(d,\alpha)N^{14}$ reaction was found from the measured particle energy by using the known reaction energy[13] and the input energy found from the (d,p) reaction.

Knowing the loss for alpha-particles of one energy, the appropriate corrections could be made to the energy of each of the alpha-groups from the silicon reaction. The fact that Q-values calculated from runs using transmission target positions agreed with Q-values from runs using reflection positions is evidence that the corrections were properly made.

The various alpha-particle groups were identified by observing the effect, on the calculated Q-value, of changing the input energy, the angle of observation or the target isotope. Shifting bombarding energy served to identify the target nucleus to within one mass number and the change of isotopic abundance made sure that the target nucleus responsible for the observed groups was actually Si^{28}. The angle shift alone is sensitive enough to distinguish between Si^{28} and Si^{29} and so gave an independent positive identification. Table I shows typical identification data; in this case for the first and second excited state groups. A change of one mass unit in the value assumed for the target nucleus makes a difference of 28 kev in the calculated excitation energy of the first state for a 40-degree change in angle. This is about nine times the experimental uncertainty.

A typical spectrum of alpha particles is shown in Fig. 1. Peak widths here are determined by energy loss in the target as other peak broadening effects are negligible by comparison. The groups leading to states in Al^{26} are numbered in order of increasing excitation energy, beginning with (0) for the ground state group.

[12] C. P. Browne and W. W. Buechner, Rev. Sci. Instr. **27**, 899 (1956).
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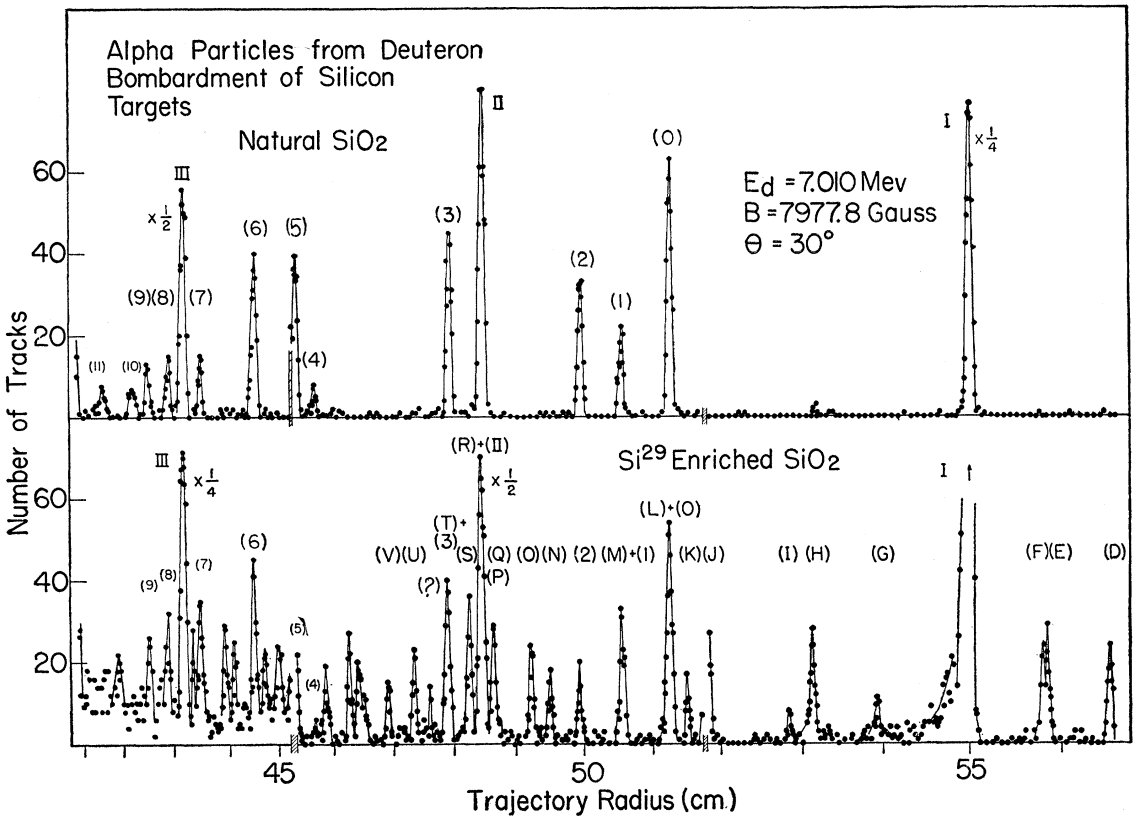

FIG. 2. Alpha particles from deuteron bombardment of a natural silicon target and a Si^{29}-enriched target. Numbered groups arise from Al^{26} levels. Lettered groups arise from Al^{27} levels. Roman numerals label groups arising from N^{14} levels.

Excitation energies in Al^{26} may be read from the sloping line using the right-hand ordinate scale.

Other particle groups are labeled with the symbol of the residual nucleus in the reaction from which they arise. Strong groups from the $O^{16}(d,\alpha)N^{14}$ reaction, leading to the ground state and second excited state are seen and a somewhat weaker group leading to the first excited state, in violation of the isotopic-spin selection rule also appears. The one group appearing from the $Si^{29}(d,\alpha)Al^{27}$* reaction leads to the two closely spaced levels at 5.4 Mev excitation.

TABLE I. Typical identification data.

Bombarding energy (Mev)	Angle of observation (degrees)	Excitation of first state[a] (kev)	Excitation of second state (kev)
5.50	30	229	418
5.75	30	(225)	417
6.00	30	229	421
6.36	30	229	420
6.50	30	230	413
6.82	30	230	419
7.01	30	228	422
7.20	30	229	418
7.29	30	232	419
7.04	30	230	419
7.04	50	231	416
7.01	60	227	418
7.04	70	(226)	417

[a] Values in parenthesis are doubtful because groups were weak.

The group leading to the first excited state of Al^{26} is seen to be about as intense as the groups leading to other states, at the bombarding energy and observation angle represented by this plot. The reaction giving rise to this group violates the isotopic-spin selection rule. Data on the yield of this group are given below and the failure to observe the group in earlier work at 90 degrees observation angle is explained.

Partial plots of spectra from similar runs appear in Fig. 1 of reference 10.

Figure 2 shows spectra obtained, under identical conditions, from a natural SiO_2 target and from a target of SiO_2 enriched in Si^{29}. By comparing relative intensities of the alpha-groups, it may be shown that particles from the $Si^{29}(d,\alpha)Al^{27}$ reaction contribute at most a few percent to the intensity of groups from the natural silicon target.

An unusually large number of determinations was obtained for most of the Q-values because many runs were needed for the yield curves and angular distributions.

Because all alpha-groups were observed simultaneously, the accuracy of the calculated excitation energies is higher than that of the individual Q-values.

TABLE II. Q-values and excitation energies for Al^{26}.

Level number[a]	Previous work: $Mg^{25}(p,\gamma)$[b] Excitation energy (Mev)	Previous work: $Si^{28}(d,\alpha)$[c] Q-value[d] (Mev)	Previous work: Excitation energy (Mev)	Present work: Number of runs	Present work: Q-value (Mev)	Present work: Excitation energy (Mev)
0		1.416	0	9	1.428[e]	0
1	0.23			12	1.199	0.229±0.003
2	0.42	0.998	0.418	8	1.010	0.418±0.002
3	1.07	0.364	1.052	7	0.369	1.060±0.002
4	1.76	−0.334	1.750	8	−0.333	1.762±0.003
5	1.86	−(0.430)[f]	(1.846)	7	−0.425	1.853±0.003
6	2.08	−0.648	2.064	10	−0.644	2.073±0.003
	2.09					
7	2.32			7	−0.940	2.368±0.003
8	2.54			6	−1.120	2.548±0.004
9				7	−1.235	2.663±0.004
10				6	−1.313	2.741±0.005
11				8	−1.488	2.916±0.006
12				5	−1.648	3.075±0.006
13	3.16			3	−1.731	3.160±0.006
14				6	−1.979	3.407±0.006
15				3	−2.082	3.510±0.010
16				3	−2.170	3.596±0.010
	3.67					
	3.76					
	4.55					
	5.16					

[a] Level numbers correspond to peak labels of Figs. 1 and 2.
[b] See reference 7 of text.
[c] Reference 1 of text.
[d] All ±0.008 except level 5 which is ±0.015.
[e] Ground state Q-value ±0.004.
[f] Identification of this level was doubtful in previous work.

The excitation energy depends predominantly on the distance, along the nuclear track plate, between the group in question and the ground state group. It is relatively insensitive to the input energy. The positions of the strong groups leading to the levels of lower excitation were more accurately measured than those of the weaker groups leading to levels of higher excitation. For this reason, and because fewer measurements were made of the higher levels, a larger error was assigned to these excitation energies.

Although the forbidden first excited state group was quite weak at many of the bombarding energies and observation angles, twelve runs gave peaks of sufficient height to permit good determinations of their positions. The excellent agreement among these different runs justifies the low uncertainty assigned to the excitation of this level.

Table II lists the Q-values and excitation energies measured in this experiment and also gives the values from the earlier (d,α) work[1] and from the (p,γ) work of Broude *et al.*[7] It is seen that the Q-values from the earlier (d,α) work agree very well, except for those of the ground state and second excited state where the difference is about the limit of the stated errors. The difference in ground state Q-values is reflected in the excitation energies of the earlier experiment where, except for the second excited state, groups leading to excited states could not be observed simultaneously with the ground state group. The broad range of the spectograph used in the present work permits more precise measurements of excitation energies. It is to be noted that the excitation energy of the first state, here determined to greater accuracy than before, agrees with results of other experiments.[2,3]

Excitation energies deduced from the gamma-ray measurements agree well with the present results. By measuring the ratio of the intensity of the cascade from level 6 to level 2 plus level 2 to ground state to the cascade from level 6 to level 3 plus level 3 to level 1, as a function of bombarding energy, it is found[3,8] that level 6 is actually a doublet. It is suggested that the upper member of the doublet is the second $T=1$ level in Al^{26}, which corresponds to the first excited state of Mg^{26}.

The best estimate of the position of this state is obtained by taking Kavanaugh's value of 1.022±0.006 Mev for the transition from this level to level 3 and the present value for the position of level 3. The result is 2.082±0.006 Mev. This is only 9 kev above the position of the level seen in this experiment at 2.073 Mev. A level with $T=1$ should of course give rise to, at most, a weak group from the (d,α) reaction. Furthermore, the targets used in this experiment were of such thickness that the alpha-groups corresponding to level 6 were 30 kev or more in width. Thus, the $T=1$ component of the doublet could not be observed. A separation of 9 kev between the two levels agrees with excitations of 2.08±0.01 and 2.09±0.01 Mev given by Green *et al.*[8]

The later authors suggest that a level they find at 3.16 Mev may the third $T=1$ level which is the analog to the second excited state of Mg^{26}. The appearance of this level here, in the (d,α) reaction, argues against this

suggestion. Of course there may well be a $T=1$ level close enough to the $T=0$ level at 3.160 Mev to be unresolved in the gamma-ray measurements.

An energy level diagram for Al^{26} appears in Fig. 3. Levels observed in this experiment are indicated by heavy lines. Levels not previously reported are marked with an asterisk.

Energy levels of Al^{27} may be found from the $Si^{29}(d,\alpha)Al^{27*}$ reaction. Data from the bombardment of the Si^{29} target are presented in Table III along with the excitation energies from the $Al^{27}(p,p')Al^{27*}$ experiment.[14] Because only one run was made and this with the target in the transmission position, the uncertainties are rather large. In calculating excitation energies from the measured Q-values a ground state Q-value of 5.994 ± 0.011 Mev was used.[15] It is seen that the excitation energies agree within the errors of the two experiments. A new level is observed at an excitation energy of 5.745 ± 0.012 Mev. A group appeared at the proper position for this level in one of the (p,p') runs but was too weak to be identified. Eight new levels above those measured in the (p,p') experiment are found and are listed in the table. There may well be other levels in this region which are unresolved or are of too low yield to be seen here.

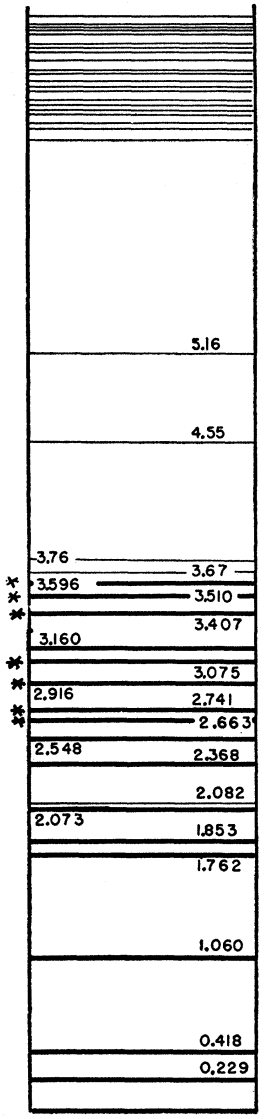

FIG. 3. Energy levels of Al^{26}. Heavy lines indicate levels observed in this experiment. Asterisks mark levels not previously reported. For details of levels at high excitation see references to gamma-ray work cited in text.

TABLE III. Q-values and excitations energies for Al^{27}.

Level designation[a]	$Al^{27}(p,p')$ excitation energy all ±0.006 (Mev)	Q-value all ±0.012 (Mev)	$Si^{29}(d,\alpha)$ excitation energy[b] all ±0.012 (Mev)
A	0.842		
B	1.013		
C	2.213		
D	2.732	3.265	2.729
E	2.977	3.023	2.971
F	3.001	c	
G	3.677	2.331	3.663
H	3.954	2.054	3.940
I	4.054	1.950	4.044
J	4.403	d	
K	4.505	1.495	4.499
L	4.576	e	
M	4.807	e	
N	5.150	0.849	5.145
O	5.242	0.759	5.235
P	5.410	f	
Q	5.425	0.574	5.419
R	5.491	g	
S	5.544	0.457	5.537
T	5.659	e	
T'		0.249	5.745
U	5.821	0.174	5.820
V	5.951	0.041	5.953
W		-0.080	6.074
X		c	
Y		-0.160	6.154
Z		-0.270	6.264
A'		-0.533	6.527
B'		-0.602	6.596
C'		-0.770	6.764
D'		-0.818	6.812
E'		-0.995	6.989

[a] Designation is that of reference 14 and also Fig. 2 for levels found in the $Al^{27}(p,p')$ experiment. Other levels not previously reported.
[b] Ground state Q-value of 5.994 ± 0.011 Mev used.[13]
[c] Not resolved from preceding group.
[d] Obscured by joint in track plate.
[e] Mixed with Al^{26} group.
[f] Peak too small to measure.
[g] Mixed with N^{14} group.

III. Al^{26} MASS AND POSITION OF THE FIRST EXCITED STATE

From the ground state Q-value of 1.428 ± 0.004 Mev and the He^4-H^2 mass difference the $Si^{28}-Al^{26}$ mass

TABLE IV. Mass of Al^{26}.

Source for Si^{28} mass[a]	Li	Wapstra	Endt and Braams
Al^{26} mass (amu)	25.995095	25.995107	25.995132

[a] For the sources tabulated see references 16, 17, and 9, respectively.

[14] Browne, Zimmerman, and Buechner, Phys. Rev. **96**, 725 (1954).

[15] Van Patter *et al.*, Phys. Rev. **85**, 142 (1952).

TABLE V. $Al^{26}-Mg^{26}$ mass difference.

Method[a]	Text reference	$Al^{26}-Mg^{26}$ (Mev)	$Al^{26*}-Mg^{26}$ (Mev)
$Si^{28}-Mg^{26}$ from mass table+present Q_0	Li[16]	3.998±0.038	4.227
$Si^{28}-Mg^{26}$ from mass table+present Q_0	Wapstra[b]	4.013±0.025	4.242
$Si^{28}-Mg^{26}$ from mass table+present Q_0	Endt and Braams[c]	4.020±0.025	4.249
$Si^{28}-Mg^{26}$ from reaction chains+present Q_0	Van Patter[d]	3.999±0.010	4.228
$Mg^{26}(p,n)Al^{26*}$ threshold+present excitation	Kington[e]	3.995±0.010	4.224
$Al^{26*} \xrightarrow{\beta} Mg^{26}$ end point+present excitation	Kavanaugh[f]	3.993±0.050	4.222
$(Mg^{25}-Al^{25})(1-1/A)^{\frac{1}{3}}$	Kington[e]		4.246±0.025
$(Mg^{25}-Al^{25})(1-1/A)^{\frac{1}{3}}$	Gove,[g] Van Patter[d]		4.198±0.009

[a] Except for the last two lines method is that for obtaining $Al^{26}-Mg^{26}$. The present excitation energy is then used to find $Al^{26*}-Mg^{26}$. Line 7 is based on the $Mg^{25}(p,n)Al^{25}$ threshold, whereas line 8 is based on the $Mg^{24}(p,\gamma)Al^{25}$ and $Mg^{24}(d,p)Mg^{25}$ Q-values.
[b] See reference 17.
[c] See reference 9.
[d] See reference 13.
[e] See reference 6.
[f] See reference 3.
[g] See reference 19.

difference may be calculated. Then, knowing the Si^{28} mass, the mass of Al^{26} may be found. Table IV gives the results using several recent values for the Si^{28} mass.

For the purpose of comparison with other results, it is convenient to calculate the $Al^{26}-Mg^{26}$ mass difference. To do this it is necessary to know the $Si^{28}-Mg^{26}$ mass difference. As there are disagreements of up to 18 kev among the various mass tables,[9,16,17] the best value is perhaps obtained from sums of nuclear reaction energies.[13] Two chains of reactions may be used, one through the nuclei Si^{28}, Si^{29}, Al^{27}, Mg^{25}, Mg^{26} and the other through the nuclei Si^{28}, Si^{29}, Si^{30}, Al^{28}, Al^{27}, Mg^{24}, Mg^{25}, Mg^{26}. The average of the resulting numbers was used with the presently determined $Si^{28}-Al^{26}$ difference to give the number listed in line three of Table V. This table gives the $Al^{26}-Mg^{26}$ mass difference calculated in this way and various other ways as indicated. The agreement among the reaction data is excellent, but the more recent mass table values for $Si^{28}-Mg^{26}$ lead to somewhat too large values. It is to be noted that the error of the present measurements is small compared to most of the other errors entering in the calculations for Table V.

As a test of charge independence of nuclear forces, it is of interest to compare the calculated position of the first $T=1$ state in Al^{26} with the measured position. Following the method of Inglis[18] the expected position relative to the ground state of the isobar Mg^{26} is found from the mass difference of the mirror pair of nuclei which each have one less neutron than the isobaric pair in question; in this case $Al^{25}-Mg^{25}$. This measured mass difference is multiplied by a factor $(1-1/A)^{\frac{1}{3}}$ to allow for the reduction of Coulomb energy in the slightly bigger nucleii. Again there is considerable discrepancy in the mass differences obtained from different experiments. Kington *et al.*[6] have found the $Mg^{25}(p,n)Al^{25}$ threshold energy and hence obtained the mass difference directly. Gove *et al.*[19] have determined the $Mg^{24}(p,\gamma)Al^{25}$ Q-value. This may be combined with the $Mg^{24}(d,p)Mg^{25}$ Q-value[13] to give $Mg^{25}-Al^{25}$. The results, adjusted as above, are shown in the last two lines of Table V. It is seen that these results bracket the values from the $Mg^{26}(p,n)$ threshold measurement and the $Si^{28}(d,\alpha)Al^{26}$ Q-value plus reaction chain mass differences. Thus, there is no evidence against charge independence.

IV. YIELD CURVES AND ANGULAR DISTRIBUTIONS

Yield-curve data for the ground state group were taken with the broad-range spectograph using either nuclear track plates or a scintillation counter mounted at a fixed position on the focal surface. With the scintillation counter in place, the magnetic field was changed for each change in input energy so as to keep the ground state alpha-particle group centered on the slit of the counter. The amplified pulses were fed to two scalars with biases set to give a single channel. Pulses from any protons having the same momentum as the alphas were approximately twice as high and fell outside the channel. Pulses from deuterons were about the same height as, and were counted with, pulses from the alphas. Slit-edge scattering of the incident beam gave a small deuteron background at all momenta but this background, along with background caused by gamma rays and neutrons, was counted and subtracted from the total count. From 6.25 to 7.10 Mev points were taken about every 20 kev.

The gross structure of the yield function was measured with a series of runs using nuclear track plates for recording. These runs were taken every 250 kev (and at more frequent intervals over part of the range). As alpha tracks could be distinguished from proton, deuteron, or neutron recoil tracks, the background was essentially zero. With the plates it was practical to use long exposure times and obtain a sufficient number of tracks to make statistical uncertainties negligible. The

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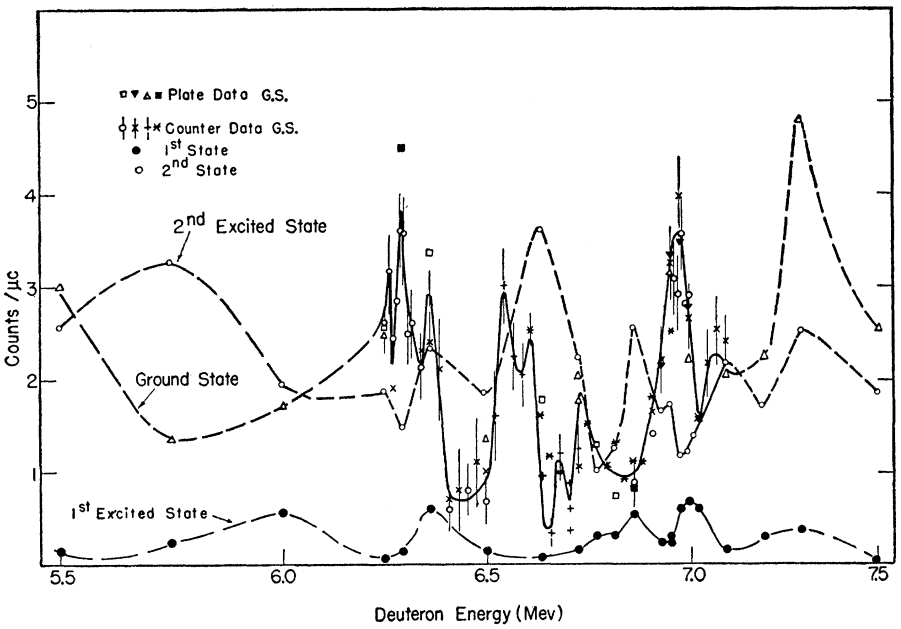

FIG. 4. Yield curves for the $Si^{28}(d,\alpha)Al^{26}$ reaction. Curves are dashed in regions where more structure is expected than is revealed by the widely spaced points. For explanation of symbols see text. Counting uncertainties for counter data are indicated by vertical bars.

plate data were used for normalization of the different counter runs, so that, in a sense, the counter data served as an interpolation between the plate data points of the yield curve. The results are shown as the curve labeled "ground state" in Fig. 4. The various symbols indicate different runs with plates and counter as noted on the figure.

Once the ground-state yield was measured, the yield of the groups leading to the first and second excited states could be plotted from the ratios of the intensities of these groups to the ground-state group. Because the three groups appear on a single plate, the only uncertainty in the ratios, aside from statistical, is the small uncertainty ($\pm 3\%$) in the variation of solid angle of the spectrograph as a function of position on the plate. The yield curves for the first and second excited states are plotted in Fig. 4.

The structure of the ground-state yield suggests that if the second excited-state yield were measured at smaller energy intervals many more fluctuations would appear. For this reason, the dashed curve drawn through the data points should be considered only a rough approximation to the true yield curve. It serves, however, to give the order of magnitude of the yield relative to the other groups.

The yields of the three alpha groups were measured as a function of angle from 15 to 130 degrees at a bombarding energy of 7.03 Mev. At this energy the yield of the forbidden group is near a maximum. Nuclear plates were used for recording and, as for the yield curve, the ground state distribution was first plotted and then the yield of the other groups was plotted from the measured ratios of intensities. Repeat runs were made to check target stability; 70 degrees was used as the angle for normalization of runs with different targets. The results are shown in Fig. 5 and are tabulated in Table VI. Counting uncertainties are indicated on the figures by the size of the symbols.

A measurement of the areas under the three angular distribution curves showed that over the range of angles from 15 degrees to 130 degrees the isotopic-spin forbidden first excited state yield is 10% of the ground state yield whereas the allowed second excited state yield is 79% of the ground state yield.

The curves show that the yield of the first excited state group vanishes at 95.5 degrees (90 degrees in the laboratory) which explain why this group was not seen in the earlier experiment done at this angle.

V. DISCUSSION

The conclusions that may be drawn from these data are the same as those drawn from the violation of the isotopic spin selection rules observed in the case of the $O^{16}(d,\alpha)N^{14}$ reaction.[10] From the yield curves and

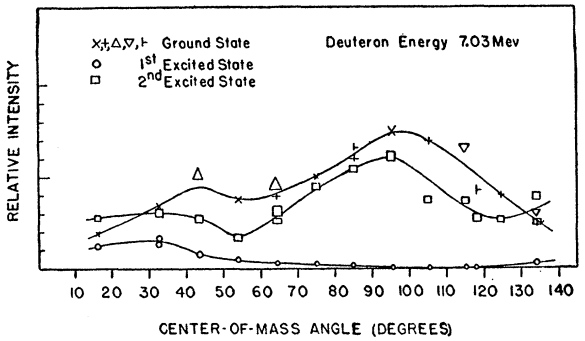

FIG. 5. Angular distributions for the $Si^{28}(d,\alpha)Al^{26}$ reaction. Different symbols on the ground state curve indicate different runs.

TABLE VI. Angular distribution for $Si^{28}(d,\alpha)Al^{26}$ at 7.03 Mev.

Center-of-mass angle (degrees)	Ground-state yield (relative to yield at 75.1°)	Yield relative to ground-state yield: First excited state	Second excited state
16.4	0.38	0.62	1.43
32.7	0.68	0.44	0.90
43.5	1.04	0.14	0.52
54.2	0.75	0.12	0.52
64.7	0.82	0.06	0.66
75.1	1.00	0.04	0.88
85.4	1.19	0.02	0.92
95.5	1.48	0.004	0.82
105.4	1.38	0.002	0.54
115.1	1.30	0.004	0.56
118.0	0.85	0.008	0.64
124.7	0.79		0.67
134.2	0.59	0.07	1.20
	Average	10.3% of ground-state yield	78.8% of ground-state yield

angular distributions it is obvious that although the $Si^{28}(d,\alpha)Al^{26}$ reaction can lead to the first excited state of Al^{26}, the yield to this state is much less than the yield to the ground or second excited state. Of course, the angular distribution would be expected to change with energy, so that a quantitative comparison of cross sections is given at only one energy by the present data. It would be desirable to have total cross sections for each group as a function of energy. A good estimate however, of the order of magnitude of the violation of the isotopic-spin selection rule, is given by these data. From the yield curve it is seen that the angular distribution was taken at an energy near a maximum in the forbidden group yield and near a minimum in the ground state yield. It would be expected therefore, that the average ratio of forbidden group yield to ground state yield is a fraction of the 10% observed at this energy. The degree of violation of the selection rule here is of the same order as that in the $O^{16}(d,\alpha)N^{14}$ reaction.[10] As in that case, the violation may be explained through mixing of $T=1$ and $T=0$ states by Coulomb forces. Not only the isotopic-spin impurity of the initial state and final state will contribute but also the impurity of the intermediate state in P^{30}. The initial state and final state wave functions are expected to contain a few percent $T=1$, and the intermediate state somewhat more.[20] The strong resonant structure of the yield curves shows that the intermediate state plays an important role. The tendency for the allowed group yields to reach a minimum when the forbidden group reaches a maximum is less pronounced here than for the $O^{16}(d,\alpha)N^{14}$ reaction. This is undoubtedly caused by a greater density and overlapping of $T=1$ and $T=0$ states in P^{30} than in F^{18} with a consequent obscuring of the effect of a $T=1$ state, once formed, to preferentially decay to the $T=1$ final state.

The appearance of the forbidden group does not contradict charge independence of nuclear forces. The position of the $T=1$ level is perhaps a better measure of charge independence than is the degree of violation of the selection rule. It was shown above that the position is that expected on the basis of charge independence within the rather large experimental errors. In this connection another determination of the $Al^{25}-Mg^{25}$ mass difference would be desirable to remove the existing discrepancies.

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[20] W. M. MacDonald, Phys. Rev. **100**, 51 (1955); W. M. MacDonald, Phys. Rev. **101**, 271 (1956).