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Excited States of Si^{29} from an Investigation of the $P^{31}(d,\alpha)Si^{29}$ and $Si^{28}(d,p)Si^{29}$ Reactions*†

P. M. ENDT,‡ D. M. VAN PATTER, W. W. BUECHNER, AND A. SPERDUTO

Physics Department and Laboratory for Nuclear Science and Engineering, Massachusetts Institute of Technology, Cambridge, Massachusetts

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The alpha-particle groups from a thin target of zinc phosphate bombarded by 1.81-Mev deuterons have been studied with a high resolution magnetic spectrograph. Eight of the alpha-groups observed have been assigned to the previously unreported $P^{31}(d,\alpha)Si^{29}$ reaction, corresponding to the ground state and seven excited states of Si^{29} in a region of excitation of 0 to 5 Mev.

From a similar investigation of the proton groups from thin targets of silicon dioxide bombarded by 1.81-Mev deuterons, ten $Si^{28}(d,p)Si^{29}$ proton groups were observed, corresponding to the ground state and nine excited states of Si^{29}. The positions of the excited states found from the $P^{31}(d,\alpha)Si^{29}$ reaction agreed within the experimental error with those obtained from the $Si^{28}(d,p)Si^{29}$ reaction. The excited states observed in Si^{29} are at 1.282, 2.038, 2.436, 3.073, 3.623, 4.078, 4.840, 4.897, and 4.934 Mev.

I. INTRODUCTION

TWO low-lying levels[1] of Si^{29} at 1.2 ± 0.2 and 2.35 Mev are excited by the beta-decay of Al^{29}. The evidence for low excited states of Si^{29} from nuclear reactions has been previously confined to the $Si^{28}(d,p)Si^{29}$ reaction. The spectrum of protons from natural silicon targets bombarded by deuterons was first reported by Pollard and Humphreys.[2] However, only an arbitrary assignment of the proton groups was possible because of the presence of three isotopes in the targets: Si^{28}, 92 percent; Si^{29}, 5 percent; and Si^{30}, 3 percent. Recently, Motz and Humphreys[3] have investigated the (d,p) reaction for the three silicon isotopes using enriched targets and range measurements. They report levels in Si^{29} at 1.29, 2.06, 2.43, 3.08, 3.60, 4.09, and 4.87 Mev. Three of these levels were found previously by Allan and Wilkinson[4] at 1.29, 2.02, and 2.41 Mev, using a natural silicon target.

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† This work was reported at the meeting of the American Physical Society in Chicago, November, 1950. Phys. Rev. **81**, 317 (1951).

‡ On leave from Physisch Laboratorium der Rijks-Universiteit, Utrecht, The Netherlands.

[1] Seidlitz, Bleuler, and Tendam, Phys. Rev. **76**, 861 (1949).

[2] E. Pollard and R. F. Humphreys, Phys. Rev. **59**, 466 (1941).

[3] H. T. Motz and R. F. Humphreys, Phys. Rev. **80**, 595 (1950).

[4] H. R. Allan and C. R. Wilkinson, Proc. Roy. Soc. (London) **A194**, 131 (1948).

Gamma-rays from the capture of slow neutrons by natural silicon have been measured by Kinsey and his co-workers[5] using a pair spectrometer. The assignment of the gamma-rays is again complicated by the presence of the three silicon isotopes, and it cannot be made with certainty until the excited states of Si^{29}, Si^{30}, and Si^{31} are established from other nuclear reactions.

In contrast to the reactions involving silicon targets, the particle groups from $P^{31}(d,\alpha)Si^{29}$ can be unambiguously associated with the energy levels of Si^{29}. Phosphorus occurs naturally as a single isotope; and, while this reaction has not been reported, the ground-state Q-value can be estimated as 8.4 ± 0.3 Mev from reported Q-values for the $Si^{28}(d,p)Si^{29}$ and $Si^{28}(\alpha,p)P^{31}$ reactions of 6.16 ± 0.06 Mev[4] and -2.23 ± 0.25 Mev.[6] The high Q-value of the $P^{31}(d,\alpha)Si^{29}$ reaction makes possible the investigation of a large region of excitation of Si^{29}.

In measurements of the type described in the following section, greater accuracy and better resolution are usually obtained with (d,p) rather than (d,α) reactions. This is largely a result of problems associated with the target. In general, for a given target thickness, the yields are greater from the (d,p) reactions, and in addition the loss and spread of energy because of the

[5] B. B. Kinsey (private communication).

[6] O. Haxel, Z. Physik **35**, 840 (1935).

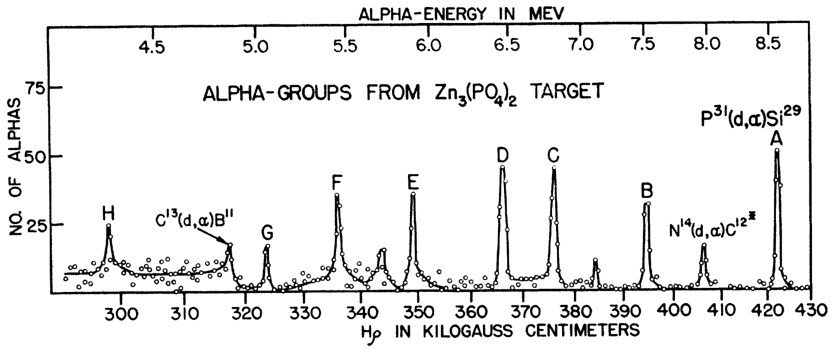

FIG. 1. Alpha-particle groups observed from a zinc-phosphate target bombarded by 1.81-Mev deuterons.

target thickness and surface are less for protons than for alpha-particles. Thus, to determine the levels in Si^{29}, we have investigated both the alpha-particles from phosphorus targets and the protons from silicon targets bombarded with deuterons, the results from the phosphorus being used to identify the proton groups from the Si^{28} isotope.

In addition to providing two independent determinations of the energies of the excited states of Si^{29}, the present measurements are of interest regarding the question[2] as to whether, for different reactions where the residual nucleus is the same, the same energy levels are excited.

II. EXPERIMENTAL PROCEDURE

The charged particles from the phosphorus and silicon targets were analyzed in the magnetic field of a 180-degree annular magnet. The analysis was at 90 degrees to the incident deuteron beam. The essential details of the experimental arrangement have been described previously,[7,8] and recent improvements in precision of measurements and calculations have been discussed in detail.[9]

In order to make a preliminary search for the $P^{31}(d,\alpha)Si^{29}$ ground-state group, a 300-kev phosphorus target was prepared by melting in a bunsen-burner flame a small amount of metaphosphoric acid on a platinum backing. A more extensive survey of the $P^{31}(d,\alpha)Si^{29}$ alpha-groups was made using a 20-kev thick zinc-phosphate target prepared by evaporation onto a platinum backing.

TABLE I. $P^{31}(d,\alpha)Si^{29}$ reaction.

Group	Q-value (Mev)	Relative intensity	Si^{29} level
A	8.170±0.020	1.0	0
B	6.885±0.020	0.9	1.286±0.010
C	6.126±0.020	1.0	2.044±0.014
D	5.727±0.020	1.4	2.443±0.015
E	5.086±0.020	0.6	3.084±0.016
F	4.539±0.020	0.9	3.631±0.017
G	4.080±0.020	0.4	4.090±0.018
H	3.221±0.020	0.6	4.949±0.020

Two targets of quartz were prepared by evaporation in vacuum onto platinum sheets. These targets were 50- and 5-kev thick for the $Si^{28}(d,p)Si^{29}$ ground-state group at 1.81-Mev bombarding energy. The thick target served for rough location of the $Si^{28}(d,p)Si^{29}$ groups, and the thin target was used for the accurate determination of Q-values.

The spectra of alpha-particles and protons were obtained by exposing a series of nuclear-track plates successively over a wide range of analyzing-magnet field strengths. The observed track-density distributions were then normalized to the same beam exposure and area of plate counted in order to make the intensities of the particle groups comparable throughout the region surveyed. Proton groups with energies less than 3.6 Mev were recorded in the presence of deuterons elastically scattered from the platinum backing of the target by covering the nuclear-track plates with thin aluminum foils sufficiently thick to stop the scattered deuterons.

For most of the surveys, a deuteron bombarding energy of 1.81 Mev was used, although in some cases other voltages were used either as a check on the assignment of a particular group or to change the relative positions of the groups of interest and those due to contaminations.

III. RESULTS

$P^{31}(d,\alpha)Si^{29}$ Reaction

The alpha-particle groups with energies from 4.1 to 8.9 Mev observed from the 20-kev zinc-phosphate target bombarded by 1.81-Mev deuterons are shown in Fig. 1. Several proton groups were also observed but are not plotted in the figure. A total of twelve alpha-groups of varying intensities is indicated. Eight of these groups were assigned to the $P^{31}(d,\alpha)Si^{29}$ reaction and are designated by the letters A through H. The remaining four groups were attributed to target contaminants of C^{13}, N^{14}, and Na^{23}. The two $Na^{23}(d,\alpha)Ne^{21}$ groups, occurring at Hr values of 344 and 384 kilogauss-cm, were identified from a comparison with the alpha-groups observed from a sodium-iodide target at the same bombarding energy. The background of alpha-particles between peaks appeared to increase at lower

[7] Buechner, Strait, Stergiopoulos, and Sperduto, Phys. Rev. **74**, 1569 (1948).
[8] Buechner, Strait, Sperduto, and Malm, Phys. Rev. **76**, 1543 (1949).
[9] Strait, Van Patter, Buechner, and Sperduto, Phys. Rev. **81**, 747 (1951).

Hr values, which can be largely accounted for by the presence of alpha-particles from polonium contamination in the target and camera chambers.

In Table I are listed the measured Q-values for the $P^{31}(d,\alpha)Si^{29}$ alpha-particle groups and the resulting positions of the Si^{29} levels. The observed relative intensities at 1.81-Mev deuteron bombarding energy are also given. Because of variations in target thickness and secondary electron emission with bombardment, these relative intensities are only approximate.

For reasons that have been mentioned, it is more convenient to obtain accurate values for the Si^{29} levels from the $Si^{28}(d,p)Si^{29}$ reaction. Hence, no intensive effort was made to use a thinner target or to eliminate the effects of surface contaminants. Although various checks indicated that the effects due to these causes were not serious, a rather large uncertainty has been assigned to the measured Q-values in order to allow for these possible sources of error.

$Si^{28}(d,p)Si^{29}$ Reaction

In Fig. 2 are shown the proton groups with energies from 2.75 to 8.0 Mev observed from a 5-kev normal SiO_2 target bombarded by 1.81-Mev deuterons. As is indicated in the figure, three of these groups have been assigned to the $N^{14}(d,p)N^{15*}$ reaction,[10] and four others have been shown as arising from contaminants of D^2, C^{12}, C^{13}, and O^{16}. The identification of the two proton groups of low intensity at *Hr* values of 341 and 368 kilogauss-cm has not been definitely established. These groups have not been observed from targets prepared from SiO_2 obtained from the Stable Isotopes Division of the AEC at Oak Ridge in which the Si^{29} and Si^{30} contents were enriched relative to Si^{28}. It is concluded that they are not associated with any of the silicon isotopes and probably arise from some unknown contaminant in the quartz used for preparing the normal SiO_2 targets.

TABLE II. Q-values for $Si^{28}(d,p)Si^{29}$ groups and energy levels in Si^{29}.

Group	Rel int	Q-value (Mev)	Si^{29} level ($Si^{28}(d,p)Si^{29}$)	Si^{29} level ($P^{31}(d,\alpha)Si^{29}$)	Si^{29} level[3]
A	1.0	6.246±0.010	0	0	0
B	1.4	4.964±0.008	1.282±0.007	1.286±0.010	1.29±0.04
C	1.2	4.208±0.008	2.038±0.007	2.044±0.014	2.06±0.04
D	0.8	3.810±0.007	2.436±0.007	2.443±0.015	2.43±0.04
E	0.5	3.173±0.007	3.073±0.007	3.084±0.016	3.08±0.05
F	0.4	2.623±0.006	3.623±0.007	3.631±0.017	3.60±0.05
G	0.3	2.168±0.007	4.078±0.008	4.090±0.018	4.09±0.06
—	0.6	1.406±0.008	4.840±0.010	——	——
—	0.4	1.349±0.008	4.897±0.010	——	——
H	4.3	1.312±0.008	4.934±0.010	4.949±0.020	4.87±0.10

The remaining ten groups have been assigned to the $Si^{28}(d,p)Si^{29}$ reaction. The relative intensities of these groups were the same from both normal SiO_2 targets and from SiO_2 targets enriched in Si^{29} and Si^{30}. It is interesting to note that many of these groups have often been observed from targets other than SiO_2, including the phosphate targets used for the $P^{31}(d,\alpha)Si^{29}$ reaction. In these cases, they appear to arise from a surface contamination due to the use of silicone stopcock grease in the vacuum system. On the basis of the assignment to the $Si^{28}(d,p)Si^{29}$ reaction, the Q-values of these groups have been calculated and are tabulated in Table II. Table II also lists the observed relative intensities and the energy levels in Si^{29} to which these groups correspond.

As has been mentioned, it is possible to check the assignment of these groups to the Si^{28} isotope, since the levels in Si^{29} calculated on this assumption should agree with the values obtained from the $P^{31}(d,\alpha)$ reaction. The positions of the Si^{29} levels obtained from this latter reaction are also included in Table II. It can be seen that there is agreement within the experimental error between the positions of the levels corresponding to the proton groups marked *A* through *H* in Fig. 2 and those corresponding to the alpha-particle groups marked *A*

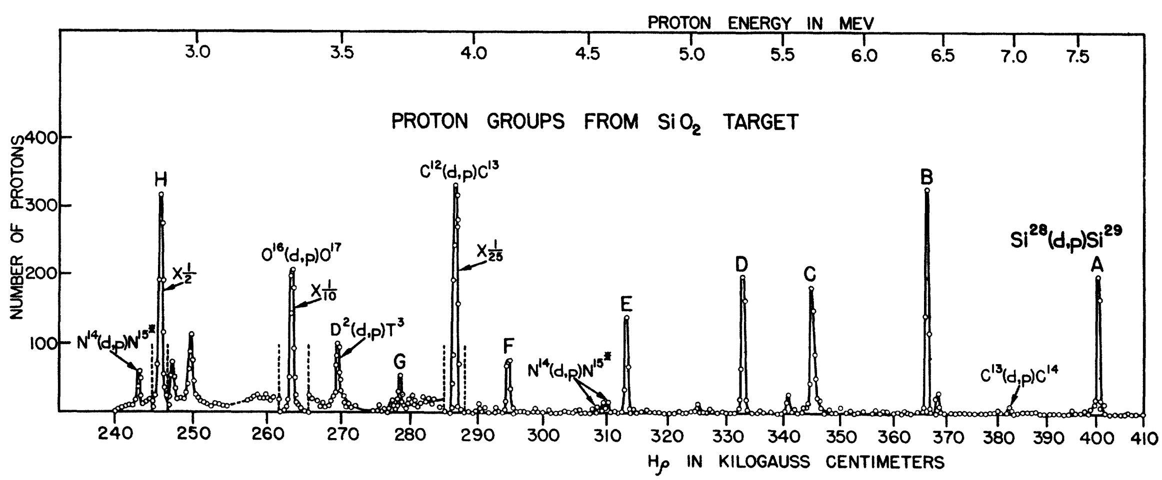

FIG. 2. Proton groups observed from a natural quartz target bombarded by 1.81-Mev deuterons.

[10] R. Malm and W. W. Buechner, Phys. Rev. 80, 771 (1950).

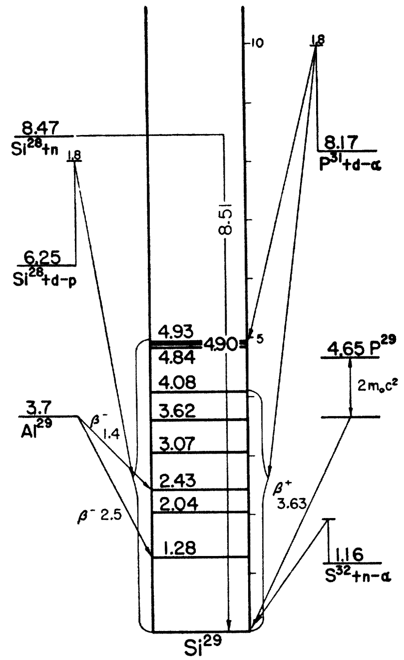

FIG. 3. Energy-level diagram for Si^{29}.

through H in Fig. 1. The discrepancy of 15 kev for the levels corresponding to the two groups marked H can be attributed to the uncertainty in determining the peak position of the $P^{31}(d,\alpha)Si^{29}$ group H in the presence of a high background. The fact that no $P^{31}(d,\alpha)Si^{29*}$ alpha-particle groups were observed which would correspond to the proton groups at 247.4 and 249.7 kilogauss-cm does not rule out the possibility that these groups may be assigned to Si^{28}, since they are approximately one-tenth the intensity of proton group H. The intensities of these two groups were found to be the same, relative to the group H, from both normal SiO_2 and enriched SiO_2 targets. In addition, the shift in energy of these two groups was the same within the limits of measurement as the group H when the bombarding energy was changed from 1.8 to 2.0 Mev, indicating that the target mass responsible for these two groups does not differ by more than five mass units from Si^{28}.

IV. CONCLUSIONS

An investigation of the $P^{31}(d,\alpha)Si^{29}$ and $Si^{28}(d,p)Si^{29}$ reactions by magnetic analysis has shown eight particle groups from both reactions which correspond to the ground state of Si^{29} and the same seven excited states. The positions of the excited states found from the two reactions agree within the experimental error. However, the results from the $Si^{28}(d,p)Si^{29}$ reaction are considered to be more accurate. Two additional proton groups were observed for which no corresponding alpha-particle groups were found. However, their low intensity, relative to the other proton groups, and the presence of a high background in the corresponding portions of the alpha-particle spectrum prevent the elimination of the possibility that alpha-particle groups may have been present which were associated with the excitation of these two additional states in Si^{29}. An energy-level diagram for Si^{29}, incorporating these results, is shown in Fig. 3.

The positions of the Si^{29} levels found from these measurements are in good agreement with the recently reported range measurements of Motz and Humphreys,[3] which are included in Table II. However, the present ground-state $Si^{28}(d,p)Si^{29}$ Q-value of 6.246 ± 0.010 Mev is definitely higher than their value of 6.18 ± 0.09 Mev and the earlier value of 6.16 ± 0.06 Mev found by Allan and Wilkinson.[4] A verification of the higher figure is obtained by subtracting the deuteron binding energy of 2.226 ± 0.003 Mev[11] from the gamma-ray of 8.51 ± 0.04 Mev observed by Kinsey *et al.*[5] from the neutron capture of natural silicon. This calculation leads to a predicted Q-value of 6.28 ± 0.04 Mev for $Si^{28}(d,p)Si^{29}$.

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[11] R. C. Mobley and R. A. Laubenstein, Phys. Rev. **80**, 309 (1950).