Energy Levels of the Silicon Isotopes from Inelastic Proton Scattering*

R. E. WHITE†
Laboratory for Nuclear Science, Massachusetts Institute of Technology, Cambridge, Massachusetts
(Received February 23, 1960; revised manuscript received March 24, 1960)

Energy levels of the stable isotopes of silicon, Si^{28}, Si^{29}, and Si^{30}, up to 6.5-Mev excitation have been investigated by studying the inelastic scattering of 7.5-Mev to 8.5-Mev protons from a thin silicon-dioxide target with a broad-range magnetic spectrograph. Several new levels are reported, and the significance of the Si^{28} results is discussed in regard to a previously proposed interpretation of the level spectrum.

I. INTRODUCTION

It was suggested in 1957 by Bromley *et al.*[1] that, since on a pure *j-j* coupling picture the Si^{28} core corresponds to the closing of the $d_{\frac{5}{2}}$ shell for both protons and neutrons and may, therefore, have a spherical shape, its energy-level spectrum might be expected to exhibit features characteristic of collective vibrations. Such a spectrum should show almost equally spaced levels with a spin sequence 0^+, 2^+, $(0^+2^+4^+)$, where the last three bracketed levels form a closely spaced triplet. At the time this proposal was made, accurate measurements were available only for the first excited state of Si^{28} at 1.77 Mev with a spin of 2^+.[2] The second excited state had been reported at 4.64±0.02 Mev with $J \geq 3$ with a possible further level at 4.62 Mev with $J \leq 2$.[1] This gave the ratio of the energy of the second to first excited states as 2.5 with a possibility of the correct spin sequence except for the absence of a 0^+ state at 4.6 Mev. More recently, Araujo[3] has again suggested that the 1.77-Mev state may be a quadrupole vibrational state.

The experiment to be described was aimed initially at clarifying the Si^{28} level sequence and especially the structure of the 4.6-Mev state by observing protons inelastically scattered from Si^{28} with a broad-range magnetic spectrograph having an energy resolution of better than 1 part in 1000. It quickly became apparent that, using targets of natural SiO_2, proton groups were also being observed corresponding to excited states in Si^{29} and Si^{30} which have abundances of 4.7 and 3.1%, respectively. The scope of the work was therefore extended to include a study of the excited states of all three isotopes up to about 6.5-Mev excitation. Prior to this, levels had been observed up to 6.380 Mev in Si^{29} and to 5.622 Mev in Si^{30} with high accuracy through the magnetic analysis of the appropriate (d,p) reactions.[2] The present work has revealed new states in both nuclei below these energies, as well as some states at higher excitations.

II. EXPERIMENTAL DETAILS

Thin targets of natural SiO_2 were prepared by evaporating highly purified silicon dioxide from a tantalum boat in vacuum onto thin Formvar films. Some difficulty was experienced in getting sufficient silicon dioxide to evaporate because of its high boiling point, and relatively large amounts, 40 to 50 milligrams, of SiO_2 had to be used in each evaporation. However, despite the fact that the boat and its contents were heated to white heat, almost no tantalum was found in a mass analysis of the resulting targets, so that it proved to be a very satisfactory boat material in this instance. Targets used, which were 2-kev thick for 8.59-Mev protons, were exposed to proton beams from the MIT–ONR Van de Graaff accelerator.[4] The beam covered a rectangular area 0.75-mm high by 2.25-mm wide, the exposed area of the target being smeared out into a ring by continuous rotation to improve heat dissipation.

Bombarding energies of 8.588, 8.001, and 7.446 Mev were used, and the resulting proton spectra were observed at angles of 30, 50, 90, and 130 degrees with the MIT broad-range magnetic spectrograph[5] and recorded on nuclear-track plates. Details of the experimental arrangement have been published previously.[6] In nearly all cases the incident energy was determined from the observed energy of protons elastically scattered by Si^{28}. If this was not possible, the energy of a proton group corresponding to a Si^{28} excited state was used. The spectrograph can only focus particles over a range of energies varying by a factor of about 2.5, for example 7 Mev to 3 Mev and 3 Mev to 1.2 Mev, so that to cover the range of excitation up to 6.5 Mev, at least two exposures were necessary at each angle.

Exposures were also made at 90 and 130 degrees with a target enriched to 64% in Si^{29} prepared for earlier experiments in this laboratory. This target had a gold backing which gave rise to a considerable background

* This work has been supported in part with funds provided by the U. S. Atomic Energy Commission, by the Office of Naval Research, and by the Air Force Office of Scientific Research.
† Now at Atomic Energy Research Establishment, Harwell, Didcot, Berkshire, England.
[1] D. A. Bromley, H. E. Gove, and A. E. Litherland, Can. J. Phys. **35**, 1057 (1957).
[2] P. M. Endt and C. M. Braams, Revs. Modern Phys. **29**, 683 (1957).
[3] J. M. Araujo, Nuclear Phys. **13**, 360 (1959).
[4] W. W. Buechner, A. Sperduto, C. P. Browne, and C. K. Bockelman, Phys. Rev. **91**, 1502 (1953).
[5] C. P. Browne and W. W. Buechner, Rev. Sci. Instr. **27**, 899 (1956).
[6] W. W. Buechner, M. Mazari, and A. Sperduto, Phys. Rev. **101**, 188 (1956).

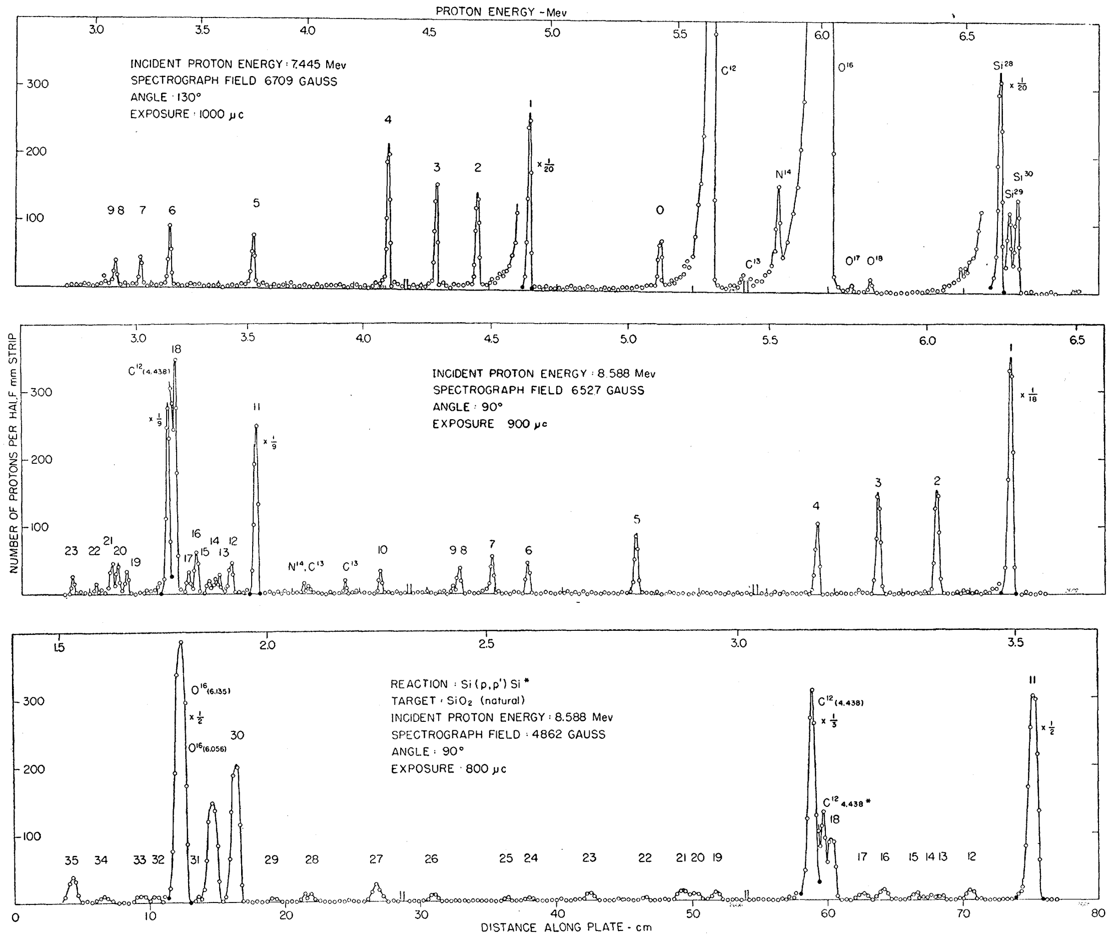

FIG. 1. Typical spectra of proton groups observed from the bombardment of a natural SiO_2 target with protons. Peaks corresponding to Si excited states are numbered and are identified in Tables I, II, and III. Peaks corresponding to excited states of an impurity nucleus are marked with the symbol for that nucleus.

of scattered protons increasing in intensity at lower proton energies. Results obtained with this target were therefore only used to confirm Si^{29} levels up to 5-Mev excitation.

III. RESULTS

Figure 1 shows typical proton spectra observed in this experiment. The distance along the plate scale refers to the distance at which proton tracks were observed on the emulsion plates relative to a fixed zero, and the intensity scale gives the number of tracks originating in each strip of emulsion 0.5-mm wide along the distance axis and 8.5-mm high. The distance scale is related to the radii of curvature, and hence the momenta of the various proton groups in the magnetic field of the spectrograph. All excitation energies quoted below are based on a calibration of this distance scale using natural polonium alpha particles of known momentum corresponding to an energy of 5.2988 Mev. Recently, a higher value of 5.3042 Mev has been suggested for this energy on the basis of some new measurements.[7] If we adopt this new value, the effect can be allowed for by increasing all excitation energies by 0.1%. Numbered peaks in Fig. 1 correspond to silicon excited states, while impurity states are marked according to their parent nuclei. The numbers 2604, etc., identify the emulsion plates used.

The group marked C^{12} 4.438* is assumed to arise

TABLE I. Si^{28} excited states.

Peak number	Present work E_x Mev	$Al^{27}(He^3,d)Si^{28}$ [a]	Previous results
1	1.775±0.006		{1.771±0.010 1.777±0.010
11	4.614±0.006	(4.617)[b]	4.617±0.010
18	4.975±0.006	4.975±0.010	
30	6.270±0.006	6.276±0.010	

[a] S. Hinds and R. Middleton, see reference 8.
[b] Normalization value.

[7] G. J. Nigh, A. H. Wapstra, and R. van Lieshout, *Nuclear Spectroscopy Tables* (North Holland Publishing Company, Amsterdam, 1959), p. 128.

from a thin film of carbon deposited during the exposure on the face of the target illuminated by the beam. Such a film would produce groups of slightly higher energy than the carbon in the target backing, since to reach the backing, the incident protons had first to pass through this film and the SiO_2 layer. A similar structure was observed on the high-energy side of the carbon elastic group measured during the same exposure, and the relative intensities of the small and large groups were similar for both the elastic and the 4.438-Mev state groups. This structure associated with C^{12} groups was observed several times in the course of this work and has also been found by other workers doing similar experiments in this laboratory. The structure is not associated with the Si^{28} 4.975-Mev state group, since this group was seen to be single in measurements at other angles where it was well resolved from the C^{12} 4.438-Mev state group.

Excited-state energies determined in this experiment are listed in Tables I, II, and III for Si^{28}, Si^{29}, and Si^{30}, respectively. Also given there are previous results taken from reference 2 and any new results since 1957 of high accuracy. The most important new measurements for Si^{28} are those of Hinds and Middleton[8] who have observed twenty-nine states up to 10.4 Mev through the $Al^{27}(He^3,d)Si^{28}$ reaction using 9.16-Mev He^{3++} ions and a broad-range magnetic spectrograph. Their values, normalized to 4.617 Mev for the second excited state, agree well with those determined here. They have also studied the $Al^{27}(He^3,p)Si^{29}$ and $Si^{28}(d,p)Si^{29}$ reactions and find states up to 7.1 Mev. The values found here up to 6.6 Mev are in good agreement with their results. De S. Barros *et al.*[9] report values for the first four states of Si^{30} from the $Al^{27}(\alpha,p)Si^{30}$ reaction, but there is a significant discrepancy between their results and the values found here.

TABLE II. Si^{29} excited states.

Peak number Fig. 1	Present work E_x Mev	$Si^{28}(d,p)Si^{29}$ E_x Mev[b]	$Al^{27}(He^3,p)Si^{29}$ E_x Mev[b]	Previous results E_x Mev[c]
0	1.278 ±0.006	1.270±0.010		1.278±0.007
2	2.027 ±0.006	2.028±0.010		2.027±0.007
4	2.424 ±0.006	2.426±0.010		2.426±0.007
5	3.064 ±0.006	3.067±0.010		3.070±0.007
7	3.620 ±0.006	3.621±0.010		3.621±0.007
10	4.079 ±0.006	4.074±0.010		4.078±0.008
12	4.735 ±0.006	4.735±0.010	4.736±0.010	
15	4.833 ±0.006	4.833±0.010	4.837±0.010	4.840±0.008
16	4.891 ±0.006	4.890±0.010	4.887±0.010	4.897±0.008
17	4.930 ±0.006	4.924±0.010	4.920±0.010	4.934±0.008
20	5.244 ±0.007	5.251±0.010	5.250±0.010	
21	5.274 ±0.007	5.280±0.010	5.280±0.010	
25	5.646 ±0.007	5.644±0.010	5.646±0.010	
26	5.804 ±0.007	5.806±0.010	5.808±0.010	
27	5.937 ±0.007	5.942±0.010	5.945±0.010	5.946±0.009
28	6.098 ±0.007	6.101±0.010	6.102±0.010	6.105±0.009
29	6.189 ±0.007	6.186±0.010	6.184±0.010	
31	6.380 ±0.007	6.370±0.010	6.371±0.010	6.380±0.009
		6.414±0.010	6.412±0.010	
32	6.482[a]±0.007	6.490±0.010	6.487±0.010	
33	6.515[a]±0.007	6.512±0.010	6.512±0.010	
34	6.609[a]±0.007	6.606±0.010	6.606±0.010	
35	6.695[a]±0.007	6.689±0.010	6.685±0.010	

[a] Observed at 90 degrees only and identified only by comparison with levels reported in (b).
[b] S. Hinds and R. Middleton, see reference 8.
[c] See reference 2.

TABLE III. Si^{30} excited states.

Peak number Fig. 1.	Present work E_x Mev	$Al^{27}(\alpha,p)Si^{30}$ E_x Mev[b]	Previous results E_x Mev[c]
3	2.232 ±0.006	2.258±0.006	2.239±0.020
6	3.493 ±0.006	3.518±0.007	3.515±0.016
8	3.765[a]±0.006		
9	3.785 ±0.006	3.798±0.009	3.786±0.020
13	4.805 ±0.006		
14	4.827 ±0.006	4.85 ±0.010	4.83 ±0.02
			5.075±0.015
19	5.220[a]±0.007		
			5.28 ±0.02
22	5.365 ±0.007		
23	5.477 ±0.007		5.497±0.015
24	5.610 ±0.007		5.622±0.015

[a] Still tentative.
[b] See reference 9.
[c] See reference 2.

It can be seen from Fig. 1 that the proton groups corresponding to excitations in Si^{29} and Si^{30} above 5 Mev were very weak, and it is possible that not all the states have been observed. The 6.414-Mev state in Si^{29} reported by Hinds and Middleton was obscured at 90 degrees by an O^{16} excited-state group, and, since this excitation was not reached at any other angle, this state was not identified. No attempt has been made so far to study these higher excitations with enriched Si^{29} or Si^{30} targets as they are currently being investigated through (d,p) reactions.

The errors quoted in the tables are mostly systematic errors arising from uncertainties in the polonium calibration. Excitation energies calculated from different measurements usually agreed to within 3 kev. Efforts are being made in this laboratory to reduce both the uncertainty in the alpha energy and some uncertainties which at present exist regarding possible effects of the preparation method of polonium sources on the observed energy. As in previous measurements, the third-height point on the high-energy side of each group was taken as representing the corresponding particle energy.

IV. DISCUSSION

From the present work it appears that the 4.614-Mev state in Si^{28} is single. The solid curve in Fig. 2 shows the proton group, observed at 30 degrees to the incident beam, which corresponded to Si^{28} being left in this state. The proton intensity is plotted against proton energy and against excitation energy in Si^{28}. The 30-degree results were chosen because at forward angles the groups are considerably narrower than at backward angles as a result of the target geometries used in these measurements. At forward angles the incident and

[8] S. Hinds and R. Middleton, Atomic Weapons Research Establishment, Aldermaston, Berkshire, England (private communication).

[9] F. de S. Barros, P. D. Forsyth, A. A. Jaffe, and I. J. Taylor, Proc. Phys. Soc. (London) A73, 793 (1959).

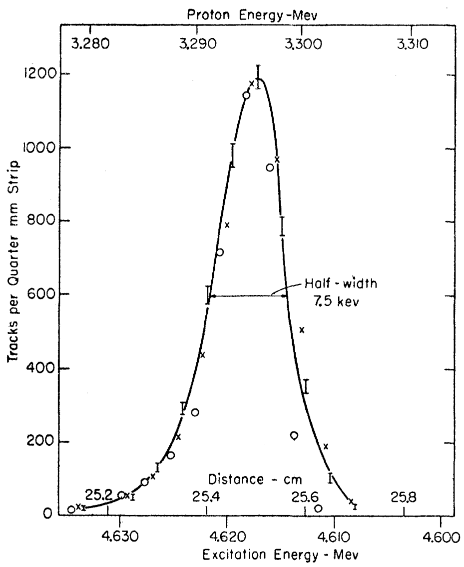

FIG. 2. Peak shape for Si^{28} 4.614-Mev state group. The solid curve shows the proton group observed at 30 degrees which corresponded to the formation of the Si^{28} 4.614-Mev excited state. The bombarding energy used was 8.000 Mev. Statistical errors are indicated by vertical bars. The crosses and circles correspond to counts for the Si^{28} 4.975-Mev state group and the C^{12} 4.438-Mev state group, respectively, observed in the same measurement. Their significance is explained in the text.

scattered protons entered and left opposite faces of the target so that, for all groups, the target and backing had to be traversed. The rate of energy loss of protons in the target and backing does not change very quickly in the energy range 3 to 8 Mev so that all groups on the plates should have had very nearly the same width no matter in what part of the target or backing the nuclei giving rise to these groups were situated. This was useful in the 30-degree case, since it allowed the shape of the Si^{28} 4.614-Mev group to be compared with any strong proton group of well-defined shape whether it corresponds to a Si^{28} state or not. The dispersion varies slowly along the plates so that there is a superimposed slow variation of peak widths as may be seen in Fig. 1. For this reason, only two strong groups in the neighborhood of the 4.614-Mev state group, one corresponding to the Si^{28} 4.975-Mev state, the other to the C^{12} 4.438-Mev state were considered. Assuming that both of these groups correspond to single states, plots of these groups were superimposed on the 4.614-Mev state group by normalizing them to the maximum of this latter group and plotting them on the same distance scale. The corresponding points are shown in Fig. 2 as crosses and circles for the Si^{28} 4.975-Mev state group and the C^{12} 4.438-Mev state group, respectively. It is seen that the three groups do have very nearly the same half-width, equivalent to 7.5 kev in proton energy, and the same detailed shape. It seems probable therefore that the 4.614-Mev state group also corresponds to a single state, unless any superimposed group is very weak or has an energy only a few kev different from 4.614 Mev, since the resolution was about 5 kev.

At angles of 90 degrees or more, it is customary to observe scattered protons from the same face of the target as is exposed to the beam. This reduces energy losses in the target for the highest energy protons in each group. This is important since the leading edge of the group defines the energy assigned to the group. It also increases the widths of the groups because, in extreme cases, reactions may now occur at the illuminated face of the target with zero energy loss in the target, or they may occur deep in the target with an energy loss for both the incident and scattered protons. At 90 degrees the groups now have a width greater than that observed at forward angles by an amount equal to twice the target thickness in kev times the secant of the angle of incidence. The latter product is given by the difference in input energies calculated using the Si^{28} elastic group and the main C^{12} elastic group from carbon in the target backing, since these C^{12} elastically scattered protons have to pass through the silicon before and after scattering. This difference was about 6 kev, and indeed the mean width of the groups near the 90-degree 4.614-Mev Si^{28} state group was just 13 kev as it should have been. The half-width of the 4.614-Mev state group was also 13 kev (No. 11 in Fig. 1), indicating that there was no strong second group nearby.

If the Si^{28} 4.614-Mev state is a member of a vibrational triplet, its spin J should be 0^+, 2^+, or 4^+, as stated previously. The information available as to the spin of this state is conflicting. Rubins[10] assigns a value between 1^- and 4^- from angular-distribution measurements on the $Al^{27}(d,n)Si^{28}$ reaction, but Hinds and Middleton find that the proton captured into this state in the $Al^{27}(He^3,d)Si^{28}$ reaction carries in two units of angular momentum so that the spin of the state is between 0^+ and 5^+. An experiment is in progress in this laboratory to determine this spin from $Si^{28}(p,p'\gamma)$ angular-correlation measurements.

If the observed 4.614-Mev state has $J=0$, it is possible that protons leaving Si^{28} in this state emerge with $l=0$. If protons leaving the 2^+ and 4^+ members of the triplet would have to have $l=2$ and $l=4$, respectively, the intensity of the corresponding proton groups would be no more than 9 and 0.03%, respectively, of the intensity of the $l=0$ group because of angular-momentum barrier effects[11] alone. It is doubtful whether this experiment would have resolved a second group within a few kev of the main one and with only 9% relative intensity, so that, if these conditions prevail, the present measurements do not rule out the vibrational interpretation of the Si^{28} states. In the $Al^{27}(He^3,d)Si^{28}$ reaction, however, it is possible to form $J=0^+$, 2^+, and 4^+ states in Si^{28} by capturing $l=2$

[10] A. G. Rubin, Phys. Rev. **108**, 62 (1957).
[11] W. T. Sharp, H. E. Gove, and E. B. Paul, Atomic Energy of Canada Limited, Report No. AECL 268.

protons so that, unless there is some other factor strongly inhibiting the formation of two members of the triplet, three groups should be observed at about 4.614-Mev excitation. Hinds and Middleton report that the group they observe is single. High-resolution studies of the $P^{31}(p,\alpha)Si^{28}$ reaction[12] also reveal only a single group corresponding to this excitation, but here again angular-momentum barrier effects could reduce the intensity of groups from nonzero spin states. The present evidence seems to indicate that there is probably only a single Si^{28} state at 4.614-Mev excitation with no other states between 4.614 and 4.975 Mev.

One state tentatively assigned to Si^{30} at 5.075 Mev from investigations of the $Si^{29}(d,p)Si^{30}$ reaction[13] has not been observed here. It would be obscured in Fig. 1 by the tail of the C^{12} 4.438-Mev state group, but the corresponding region of a spectrum taken at 130 degrees is shown in Fig. 3. In no case was a group seen at the appropriate distance for 5.075-Mev excitation in Si^{30} of intensity comparable to adjacent Si^{30} or Si^{29} groups. Preliminary analysis of recent $Si^{29}(d,p)Si^{30}$ data taken at 7.5 Mev also shows no Si^{30} state at this energy, although it does confirm the existence of states at excitations near all of those listed in column 2 of Table III. Accurate values for the energies of these states from the (d,p) results are not yet available.

An attempt was made to check on a recent suggestion by Sheline *et al.*[14] that it might be possible to obtain some indication of the J values of the states of residual nuclei observed in the type of experiment described here from the measured intensities of the corresponding particle groups. The suggestion is that, after correction for Coulomb effects, the most significant factor governing the intensities of the various groups should be a $(2J+1)$ statistical weight factor, where J refers to the residual nucleus state. Intensities divided by $(2J+1)$ should then give nearly the same quotient for all groups when the correct J values are chosen.

It seemed feasible to apply this to groups corresponding to states in Si^{29}, since spins are known for several states. It soon became apparent that agreement between values of intensity divided by $(2J+1)$ was very poor, unless it was assumed, as is almost certainly correct, that the various proton groups could be associated with different l values. If this has to be allowed, it is felt that it is not justifiable to test the method in this case, because the barrier penetrability for the scattered protons is strongly l dependent for all observed groups, and the true l values are not known. It should be pointed out that this is a general criticism of the method, especially for alpha particles, unless the outgoing particle energy is well above the barrier maximum, in which case the penetrability is almost independent of l.

[12] P. M. Endt and C. H. Paris, Phys. Rev. **106**, 764 (1957).
[13] D. M. Van Patter and W. W. Buechner, Phys. Rev. **87**, 51 (1952).
[14] R. K. Sheline, H. L. Nielsen, and A. Sperduto, Nuclear Phys. **14**, 140 (1959).

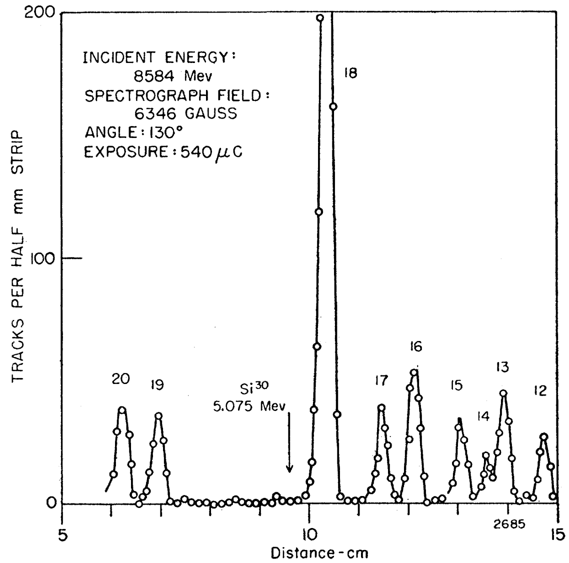

FIG. 3. The section of a proton spectrum observed at 130 degrees to an 8.584-Mev proton beam incident on a natural SiO_2 target, which should contain the proton group corresponding to the formation of Si^{30} at 5.075-Mev excitation. The expected position of this group is indicated by an arrow. Group numbers correspond to those in Fig. 1.

ACKNOWLEDGMENTS

The author would like to thank Professor W. W. Buechner very sincerely for permitting him to carry out research in this laboratory and also to acknowledge the cooperation of the whole staff. Special thanks are due to the track-counting group for their meticulous and patient work.

Note added in proof.—The spin of the 4.975-Mev state in Si^{28} is now known to be 0^+ (H. E. Gove, private communication), while there is some evidence from studies of the $Al^{27}(p,\gamma)Si^{28}$ reaction (P. M. Endt and A. Heyligers, to be published) that the spin of the 4.612-Mev Si^{28} state is 4^+.