PHYSICAL REVIEW VOLUME 187, NUMBER 4 20 NOVEMBER 1969

Study of the $Al^{27}(He^3, p)Si^{29}$ and $Al^{27}(He^3, p\gamma)Si^{29}$ Reactions*

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(Received 28 May 1969)

The levels of Si^{29} have been studied by measuring angular distributions of the $Al^{27}(He^3, p)Si^{29}$ reaction. A few states, in particular the level at 8.310 MeV (the analog of the Al^{29} ground state), were strongly excited with an orbital angular momentum transfer $L=0$ leading to states with $J=\frac{3}{2}^+$, $\frac{5}{2}^+$, and possibly $\frac{7}{2}^+$. The γ decay of some of these levels has been studied by p-γ coincidences. They all showed a very similar γ decay, namely, a preference to decay to those few positive-parity states that are also strongly populated in the (He^3, p) reaction. From the radiative decay of the 8.310-MeV level and other evidence, we conclude that the $\frac{5}{2}^+$ state at 4.906 MeV contains the major portion of the antianalog strength. The coincidence data also contained events from $Al^{27}(He^3, d\gamma)Si^{28}$. Analysis of these results showed that it was consistent with previous measurements.

I. INTRODUCTION

RECENTLY, it has been established[1,2] that (He^3, p) reactions at bombarding energies above 10 MeV proceed mainly through direct reaction processes. The neutron-proton pair from the incident He^3 particle is captured by the target nucleus either in the singlet state with spin $S=0$ and isospin $T=1$, or in the triplet state with $S=1$, $T=0$. Yoshida's calculations for two-nucleon transfer reactions[3] have shown that in the case of the (t, p) reaction the two neutrons in the singlet state are captured predominantly with a total angular momentum $L=0$ leading to the ground state or low-energy states of the final nucleus because of two-particle correlation effects. This result should be directly applicable to (He^3, p) reactions in which the deuteron is absorbed in its singlet state. Therefore, one can expect that the analog state in the final nucleus should be strongly excited by an $L=0$ transfer in the (He^3, p) reaction. Indeed, a number of analog states have been successfully identified this way; examples are given by Nolen *et al.*[4]

Since the Al^{27} ground state has $J=\frac{5}{2}^+$ and $T=\frac{1}{2}$, one would similarly assume that in the $Al^{27}(He^3, p)Si^{29}$ reaction the lowest $J=\frac{5}{2}^+$, $T=\frac{3}{2}$ state in Si^{29} (the isospin analog of Al^{29}) would be strongly excited. This analog state lies at $E_x=8.31$ MeV in Si^{29}. In contrast, one anticipates that the capture of the proton-neutron pair in its triplet state ($S=1$ and $T=0$) will populate a number of $T=\frac{1}{2}$ states in Si^{29} relatively strongly. Since the deuteron has spin $S=1$, these states will have one of the following spin assignments: $J=\frac{3}{2}^+$, $\frac{5}{2}^+$, and $\frac{7}{2}^+$ with $T=\frac{1}{2}$. We therefore expect that besides the analog state at $E_x=8.31$ MeV, a number of $T=\frac{1}{2}$ levels in Si^{29} with $J=\frac{3}{2}^+$, $\frac{5}{2}^+$, and $\frac{7}{2}^+$ should be reasonably well excited by the (He^3, p) reaction. They all should be well described by a one-hole two-particle (1h-2p) configuration.

We decided to study these states in greater detail by measuring their γ decay, since the emitted γ rays were expected to reflect the 1h-2p character of these levels. In addition, we were especially interested in the γ-ray decay of the analog state. It has recently been demonstrated[5,6] that in the *sd*-shell nuclei, strong $M1$ γ-ray transitions occur between the analog state with isospin T and its antianalog, the state having a similar nucleon configuration but with isospin $T_0=T-1$. Erné[5] has shown that in *sd*-shell nuclei such strong $M1$ transitions can be expected between nucleon configurations with an unpaired $f_{7/2}$ nucleon coupled to the core to produce total isospin $T=T_{core}+\frac{1}{2}$ and $T=T_{core}-\frac{1}{2}$. On the other hand, for an unpaired $d_{3/2}$ nucleon whose angular momentum is opposite to the spin direction, such $M1$ transitions are expected to be much weaker.[7,8] Indeed the analog state in Ca^{41} at 5.83 MeV (which has an unpaired $d_{3/2}$ hole and spin assignment $J=\frac{3}{2}^+$, $T=\frac{3}{2}$) shows only a very weak γ-ray transition to its antianalog at 2.017 MeV with $J=\frac{3}{2}^+$, $T=\frac{1}{2}$; it has an intensity $\lesssim 7\%$ of the total decay rate of this particular level.[9]

In the present experiment, we studied the γ-ray decay of the analog state in Si^{29}. This state consists of an unpaired $(d_{5/2})^{-1}$ proton hole coupled to two nucleons in either the $s_{1/2}$ or $d_{3/2}$ shell with $J_{core}=0$, $T_{core}=1$ to produce isospin assignment $\frac{5}{2}^+$, $T=\frac{3}{2}$. In this case, the mag-

* Work performed under the auspices of the U.S. Atomic Energy Commission.

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netic moments of the spin and the orbital motion of the $d_{5/2}$ hole add and a relatively strong $M1$ transition to the antianalog is expected[10]—much stronger than in the case of Ca^{41}.

In order to identify the 1h-2p levels in Si^{29} formed by deuteron absorption with $L=0$, we used a magnetic spectrograph to measure the angular distribution of the $Al^{27}(He^3, p)Si^{29}$ reaction leading to levels in Si^{29} up to an excitation energy of about 8.5 MeV. The reaction goes presumably through a direct-reaction process and exhibits angular distributions that show characteristic patterns for the different values of the orbital angular momentum transfer L. Since the differential cross sections for processes with $L=0$ are expected to be large at the far-forward angles, these particular states can be selected preferentially by placing the proton detector at an angle of 0° to the incident beam. It was found that five states were populated with cross sections large enough so that coincidence measurements were feasible and the γ decay of these levels has been studied. In addition, measured angular distributions of the $Al^{27}(He^3, p)Si^{29}$ reaction have led to a number of spin and parity assignments to Si^{29} levels.

II. EXPERIMENTAL ARRANGEMENT

A. Angular Distributions of Protons

The measurements were performed with a 12-MeV-He^3 beam from the Argonne tandem Van de Graaff accelerator. An Al target of about 130 $\mu g/cm^2$ thickness was evaporated on a thin carbon-foil backing. The protons were analyzed in a broad-range magnetic spectrograph[11] and detected in nuclear emulsions (Kodak NTB 25- or 50-μ plates). The emulsion was covered with 12.5-mil-acetate foils to keep the background to a minimum and, in particular, to stop the intense deuteron groups coming from the $Al^{27}(He^3, d)Si^{28}$ reaction. The over-all energy resolution (FWHM$\approx$40 keV) was sufficient to study the proton groups of interest. The angular distributions of the protons were measured between 5° and 61°, mostly in steps of 8°. A surface-barrier detector was used to monitor the elastically scattered He^3 ions, and these data were used to normalize the proton yield at different angles.

B. Particle–γ-ray Coincidences

For these measurements, which were also performed with a 12-MeV-He^3 beam, we used the target chamber shown schematically in Fig. 1. The incident beam was collimated by a pair of circular 1/16-in. apertures, which were shielded by means of cylindrical annular masses of lead inserted in the beam tube and which were followed by a 3/32-in. aperture.

The Ge(Li) detector, together with its liquid-air

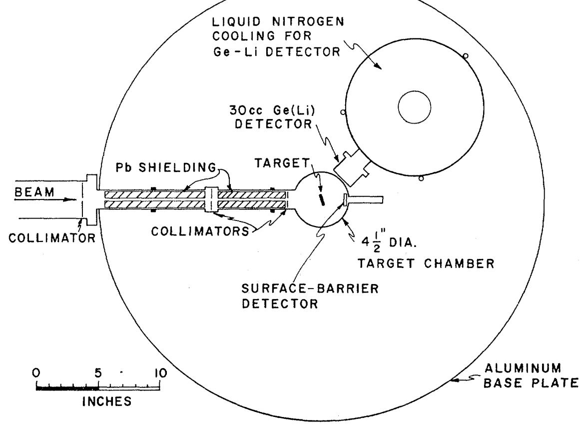

FIG. 1. Schematic arrangement of the target chamber with its particle and γ-ray detectors.

Dewar, was pegged into the base plate of the chamber at a chosen angle by means of two locating pins. The holes in the base plate were spaced at 5° intervals so the γ rays could be measured between 30° and 145° to the incident beam direction in steps of 5°. The protons were detected by a telescope of Si surface-barrier detectors whose total depletion depth was 2500 μ. The detector subtended an angular range of $\pm 10°$ relative to the target.

The chamber and its associated assembly were constructed with great care to ensure that the collimating system was aimed accurately through the center of the chamber. Similar care was taken to ensure the accurate alignment of the target and both detectors.

The pulses from the γ-ray and particle detectors were fed into a dual analog-to-digital converter (ADC) unit gated by means of a time-to-pulse-height converter which was also fed by the pulses from the γ-ray and proton detectors. The window of a single-channel analyzer was set over the coincidence peak (FWHM$\approx$ 80 nsec) so that the true p-γ coincidences were selected out of the time spectrum of the time-to-pulse-height converter. The digital outputs from the dual ADC unit (up to 1024 channels on each side) were fed to an ASI-210 computing system (described in detail elsewhere[12]), which recorded every coincidence event on magnetic tape. In addition, this system (a) accumulated and, by use of the computer memory, displayed a γ spectrum (1024 channels) in coincidence with one chosen proton group and (b) made use of an external memory to accumulate up to fifty 1024-channel spectra in coincidence with sets of proton energies previously selected by means of a light pen and an oscilloscope display of the proton singles spectrum. A 1024-channel spectrum of the coincidence particle energies was accumulated in the pulse-height analyzer itself and later transferred to the computer.

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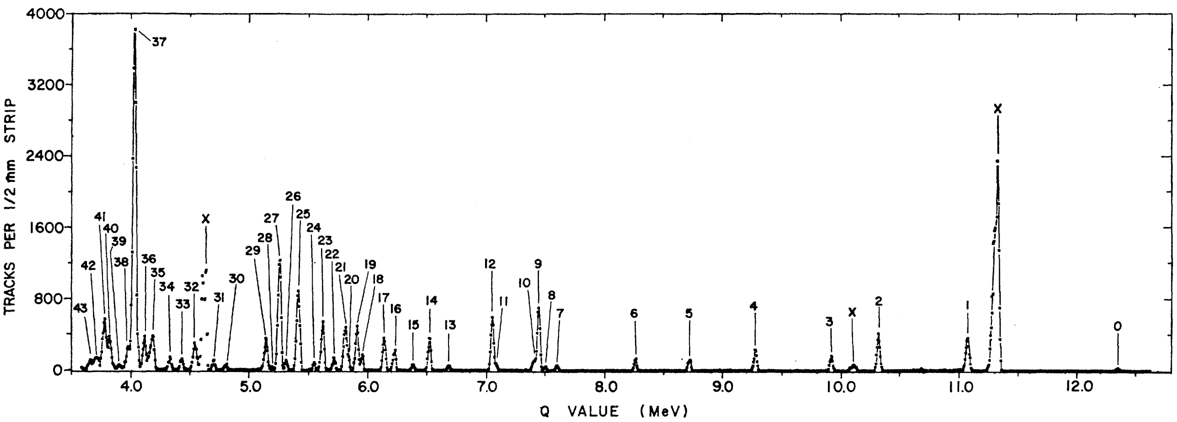

FIG. 2. Proton yield of the Al^{27} (He^3, p)Si^{29} reaction as a function of the Q value obtained by conversion from the distance along the nuclear emulsion. This spectrum was measured with the magnetic spectrograph at an angle of 5° to the incident 12-MeV-He^3 beam. The proton groups are numbered and the corresponding excitation energies in Si^{29} are listed in Table I. The groups marked X belong to protons emitted by impurities in the target. Acetate foils of 12.5 mil thickness covered the nuclear emulsion and stopped deuterons from the (He^3,d) reaction.

The external memory of the computer also served as a store for several programs used during the course of the experiment. Examples of these programs are (i) one to write the data on tape and display the data, (ii) one to make rapid analyses so that the angular correlations could be accurately ascertained during the course of the experiment, and (iii) one employing calibration routines to make rapid identification of γ energies and the positions of escape peaks in the γ-ray spectra.

The targets used in the particle–γ-ray coincidence measurements were Al foils 400 μg/cm^2 thick. The detector was covered with Au foils 170 mg/cm^2 thick in order to stop the He^3 beam and the collected charge was sent to a current integrator. Because of straggling in the Au foil the energy resolution width for the detected particles was of the order of 300 keV. The system consisting of the Au foils and the detectors (which were used without a cooling device) stopped protons of about 20-MeV energy. For this reason the protons which populated the few first excited states in Al^{29} were not at all or only incompletely stopped in the detector telescope. In earlier experiments, the single-particle spectrum measured at 0° to the incident beam was greatly disturbed by knock-on protons, i.e., by protons that arise from hydrogen contamination in the target and the Au foil, which are accelerated by the impact of the incident He^3 beam. The number of these protons was greatly reduced when a turbomolecular pump was installed directly under the target chamber. The γ-rays were detected by a 30-cm^3-Li-drifted Ge counter, which had an energy resolution width of about 5 keV for the 1.333-MeV γ-ray line of Co^{60}. Its absolute efficiency for the detection of low-energy γ-rays was measured by calibrated Co^{60}, Y^{88}, Cs^{137}, and Co^{57} sources. The efficiency for detection of high-energy γ rays was obtained by using the $Al^{27}(p,\gamma)Si^{28}$ reaction and measuring the γ rays that are emitted from the 0.992-MeV resonance. Since the relative intensities of these γ rays are known[13] and since one strong γ transition had an energy close to that of the calibrated sources, we obtained the absolute efficiency of the 30-cm^3 Ge(Li) detector for γ rays in the energy range 0.12–10.8 MeV.

III. RESULTS

A. Angular Distributions

A great number of energy levels in Si^{29} were excited in the Al^{27}(He^3, p) reaction. A typical proton spectrum observed at 5° in the spectrograph is shown in Fig. 2. Since the ground state is only weakly excited, the excitation energies were measured relative to the first excited state at 1.271 MeV. The energies were calculated from a number of measurements taken at different angles. The values agreed, in general, to within 5 keV. The energy difference between the first excited state and the ground state was determined in a long exposure. The excitation energies thus obtained are shown in Table I together with the energies given by Endt and Van der Leun.[14] One observes systematic differences of about 15–20 keV between our values and values in Ref. 14 at higher energies, but their origin has not yet been studied in detail. We believe that our values are good to about $\pm$10 keV.

Angular distributions have been obtained for most of the proton groups. In a few cases they were masked at some angle either by impurities (indicated by X in Fig. 2) or by strong neighboring proton groups. Angular distributions are plotted in Figs. 3 and 4. The loca-

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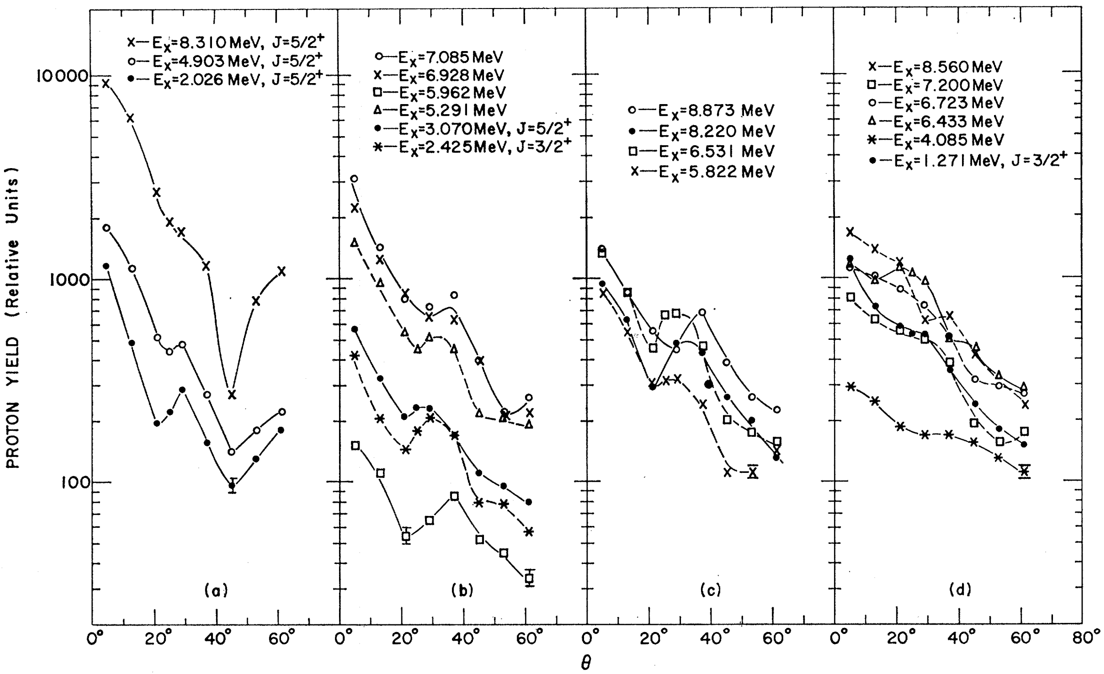

FIG. 3. Angular distributions of the reaction Al^{27} (He^3, p) Si^{29} for some levels in Si^{29}. The transitions involve angular momentum transfer $L=0$ or $L=0$ and 2. The statistical errors of the proton yields are, in general, less than a few percent of the measured values. For the very low yields the statistical errors are larger; error bars are given in the figure for some of these points where the yield was low.

tion of the plot of the angular distribution for a particular level is given in column 6 of Table I.

If one assumes a direct-interaction mechanism in the (He^3, p) reaction, one would expect to find typical angular distributions for different orbital angular momentum transfers and possibly a dependence on the spin of the final nucleus. Our attempt to fit the measured angular distributions with DWBA calculations

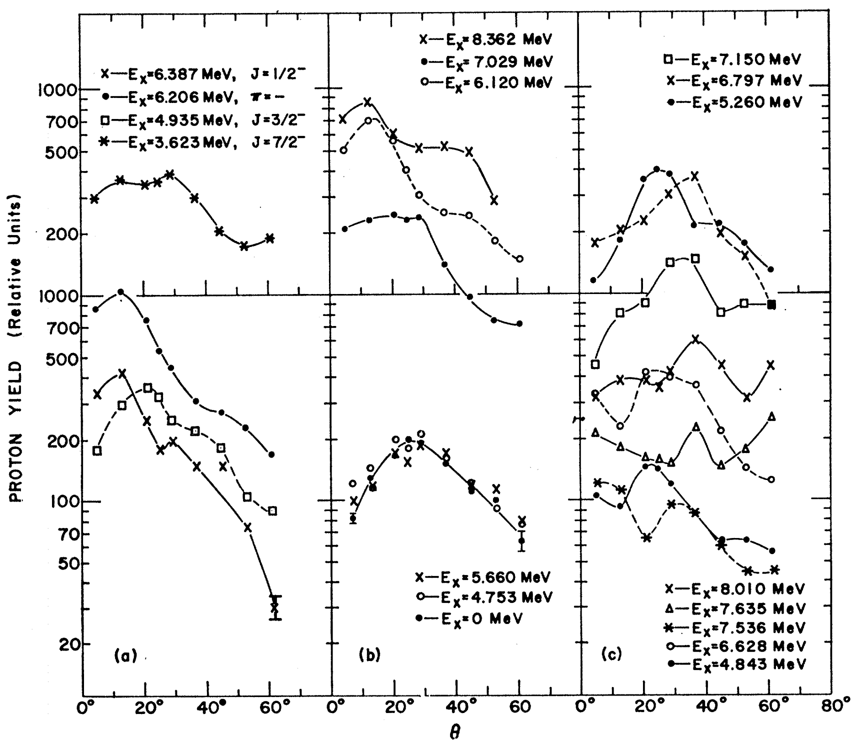

FIG. 4. Angular distributions of the reaction $Al^{27}(He^3, p)Si^{29}$ for some levels in Si^{29}. The transitions involve angular-momentum transfer $L \geq 1$. The statistical errors of the proton yields are, in general, less than a few percent of the measured values. For the very low yields the statistical errors are larger; error bars are given in the figure for some of these points where the yield was low.

TABLE I. Comparison of some pickup and stripping reactions populating levels in Si^{29}. Our results are shown in the first 6 columns. The spin and parity assignments that follow from our proton angular distributions (plotted in the figures indicated in column 6) are put in parentheses in column 5.

$Al^{27}(He^3, p)Si^{29}$ (Present experiment)						$Si^{28}(d, p)Si^{29}$ (Ref. 14)				Pickup reactions (Ref. 17)		
											Spectroscopic factors	
Peak No. 1	Yield at 5° 2	E (MeV) 3	L 4	J^π 5	Figure No. 6	E (MeV) 7	L_n 8	J^π 9	$(2J+1)\theta_n^2$ $\times 10^3$ 10	J^π 11	(d, t) 12	(He^3, α) 13
0	83	0	2	$\frac{1}{2}+$	4(b)	0	0	$\frac{1}{2}+$	46	$\frac{1}{2}+$	0.8	(0.7)
1	1240	1.271	0, 2	$\frac{3}{2}+$	3(d)	1.273	2	$\frac{3}{2}+$	70	$\frac{3}{2}+$	0.7	1.2
2	1130	2.026	0	$\frac{5}{2}+$	3(a)	2.032	2	$\frac{5}{2}+$	28	$\frac{5}{2}+$	1.7	1.7
3	420	2.425	0	$\frac{3}{2}+$	3(b)	2.427	isotr.	$\frac{3}{2}+$	<1.2	$\frac{3}{2}+$	0.17	0.21
4	565	3.070	0, 2	$\frac{5}{2}+$	3(b)	3.064	2	$\frac{5}{2}+$	16	$(\frac{5}{2}+)$	0.10	0.18
5	296	3.623	odd	$\frac{7}{2}-$	4(a)	3.623	3	$\frac{7}{2}-$	130	$\frac{7}{2}-$	0.08	0.11
6	285	4.085	(0, 2)	(+)	3(d)	4.079	isotr.	$(\frac{3}{2})$				
7	126	4.753	2	$(\frac{1}{2}+)$	4(b)	4.736						
8	102	4.843			4(c)	4.833	0	(+)				
9	1790	4.903	0	$\frac{5}{2}+$	3(a)	4.891	isotr.			$\frac{5}{2}+$	1.0	1.0
10	180	4.935	odd	(−)	4(a)	4.930	1	$\frac{3}{2}-$	120			
11	115	5.260			4(c)	5.244	isotr.					
12	1465	5.291	0	(+)	3(b)	5.274	isotr.					
13	104	5.660	2	$(\frac{1}{2}+)$	4(b)	5.646						
14	870	5.822	0	(+)	3(c)	5.804						
15	156	5.962	0	(+)	3(b)	5.937	2(1)		(8)			
16	500	6.120	odd	(−)	4(b)	6.098	1(2)		(13)			
17	885	6.206	odd	(−)	4(a)	6.187	3	$(\frac{5}{2},\frac{7}{2}-)$	43			
18	339	6.387	odd	(−)	4(a)	6.380	1	$\frac{1}{2}-$	65			
19	1150	6.433	0, 2	(+)	3(d)	6.420	(0)					
20	150	6.505				6.482	(0)					
21	1350	6.531	0	(+)	3(c)	6.515						
22	330	6.628			4(c)	6.614						
23	1250	6.723	0, 2	(+)	3(d)	6.712				$\frac{5}{2}+$	0.3	
24	164	6.797			4(c)	6.781						
25	2275	6.928	0	(+)	3(b)	6.919						
26	206	7.020	odd	(−)	4(b)	7.017						
27	3078	7.085	0	(+)	3(b)	7.074						
28	47	7.150			4(c)	7.140						
29	792	7.200	0, 2	(+)	3(d)	7.183						
						7.192						
30	125	7.536			4(c)	7.523						
31	215	7.635			4(c)	7.622						
32	828	7.794				7.785						
33	286	7.907				7.892						
34	320	8.010			4(c)	7.995						
35	1241	8.153				8.135						
						8.159						
36	906	8.220	0	(+)	3(c)	8.208						
37	9100	8.310	0	$\frac{5}{2}+$	3(a)					$\frac{5}{2}+$	2.0	1.7
38	720	8.362	odd	(−)	4(b)							
39	125	8.400										
40	940	8.520										
41	1680	8.560	0, 2	(+)	3(d)							
42	460	8.630										
43	330	8.685										
	250	8.778										
	1390	8.873	0	(+)	3(c)							

was not very successful. We obtained only the usual characteristic patterns for an $L=0$ momentum transfer, which displays a sharp increase of the yield toward small angles. For an $L=2$ transfer, the maximum yield occurs at about 30° and for an $L=1$ transfer a maximum yield occurs at some smaller angle. Some of these calculated characteristic patterns for the different momentum transfers could be confirmed by measured angular distributions, since a few states which had been studied by stripping[15,16] and pickup reactions[17] showed large spectroscopic factors. In these few cases, the nucleon configurations of the states can be reasonably well deduced, and, with the assumption of a direct-interaction mechanism, the L value in the $Al^{27}(He^3, p)Si^{29}$ reaction can be predicted. Unfortunately, measurements of γ-ray branching ratios[18] and γ-ray transition strengths,[19] even for the low-lying states in Si^{29}, indicate also more complicated properties which cannot be described by an independent-particle model with a few nucleons excited. All our conclusions deduced from the angular distribution measurements,

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shown in columns 4 and 5 of Table I, are considered therefore as tentative and are put in parentheses.

1. Orbital Angular Momentum Transfer $L=0$

Measurements of Dehnhard and Yntema[17] have shown that the two states at 2.026 and 4.903 MeV with spin assignments $T=\frac{1}{2}$, $J=\frac{5}{2}+$ and the analog state $T=\frac{3}{2}$, $J=\frac{5}{2}+$ at 8.310 MeV are reasonably well described by a 1h-2p nucleon configuration of either $(d_{5/2})^{-1}(2s_{1/2})^2$ or $(d_{5/2})^{-1}(d_{3/2})^2$ or a mixture of both configurations. If the Al^{27} nucleon configuration consists to a large extent of a hole in the $d_{5/2}$ shell, the $Al^{27}(He^3,p)$ reaction will lead to these three states in Si^{29} via an angular momentum transfer $L=0$. The angular distributions should then show a large increase in yield toward small angles. Indeed this is the case for all three states seen in Fig. 3(a), and we are rather confident that the reaction proceeds with an $L=0$ momentum transfer.

A number of similar angular distributions are plotted in Figs. 3(b) and 3(c). They all show the sharp increase in yield with decreasing angles, and we take this as an indication that an $L=0$ momentum transfer is involved. Since the state at 5.962 MeV is only weakly populated, it might be possible that compound-nucleus contributions are not negligible. We would like to mention that the strongly excited states at 7.085, 6.928, and 5.291 MeV are not seen in the (d, He^3) and (He^3, He^4) pickup reactions on Si^{30} targets.[17] This may indicate that these states are 1h-2p states with spin $\frac{7}{2}+$ or $\frac{3}{2}+$.

Angular distributions with a smaller increase in yield toward smaller angles are plotted in Fig. 3(b). It is likely that these also result from $L=0$ angular momentum transfers, but may include an $L=2$ admixture. For all distributions plotted in Figs. 3(a)–3(c), we assume that $L=0$ is dominant; but for the distributions in Fig. 3(d), mixtures of $L=0$ and $L=2$ are assumed. The L values and the parities of the final states are shown in columns 4 and 5 of Table I.

2. Odd Orbital Angular Momentum Transfer

The states in Si^{29} at energies 3.623, 4.935, 6.206, and 6.387 MeV are known to have negative parity, as indicated in column 9 of Table I. Their angular distributions [Fig. 4(a)] differ from those with momentum transfer $L=0$ and 2 in that either the yield decreases with decreasing angle and has a maximum at about 15° or it is only slightly angle-dependent at forward angles. Since similar distributions are found for the 6.120-, the 7.029-, and the 8.362-MeV states shown in Fig. 4(b), we tentatively assign negative parity to these states.

3. Orbital Angular Momentum Transfer $L=2$

In the formation of the ground state in Si^{29}, which has spin $\frac{1}{2}+$, an orbital angular momentum transfer of at least $L=2$ is involved. The reaction exhibits an angular distribution [Fig. 4(b)] which is very similar to the calculated one and also to those observed for $L=2$ transfers in the (He^3, p) reaction on different target nuclei. These distributions show a rather broad peak with maximum yield at about 20°–40°. One is therefore tempted to take the observed angular distribution for the ground state in Si^{29} as typical for a direct-interaction process with $L=2$ transfer although the cross section is small and compound-nucleus formation might have important contributions. Two other states in Si^{29} at 4.753 and 5.660 MeV have the same distributions [Fig. 4(b)]. It will be interesting to see if these spin assignments also turn out to be $\frac{1}{2}+$.

In addition to the angular distributions with characteristic patterns which indicate the L value involved and which allow at least a parity assignment, a number of other distributions with irregular shapes [Fig. 4(c)] have been measured but no parity assignments have been made.

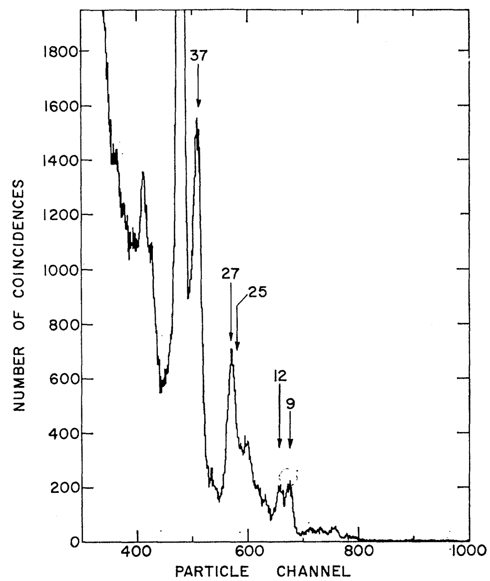

FIG. 5. Number of particles from an Al^{27} target bombarded with a 12-MeV-He^3 beam in coincidence with all γ rays emitted in the reaction. The particle detector was placed at 0°, the γ detector at 90° to the incident beam. The peak numbers given in the figure are identical with those of Table I and Fig. 2. These resonances in the (He^3, p) reaction represent excitation to states at 8.310, 7.085, 6.928, 5.291, and 4.903 MeV in Si^{29}.

B. Particle–γ-Ray Coincidences

1. $Al^{27}(He, p\gamma)Si^{29}$ Reaction

The particle spectrum in coincidence with all γ rays detected from He^3 bombardment of Al^{27} is shown in Fig. 5, where the number of coincidences measured with the γ-ray detector at 90° is plotted as a function of the particle channel number. Since all the strong proton groups are connected with $L=0$ deuteron capture, the first (primary) γ ray will be emitted in an isotropic distribution. One can expect, therefore, that the relative intensities of the proton peaks in Fig. 5

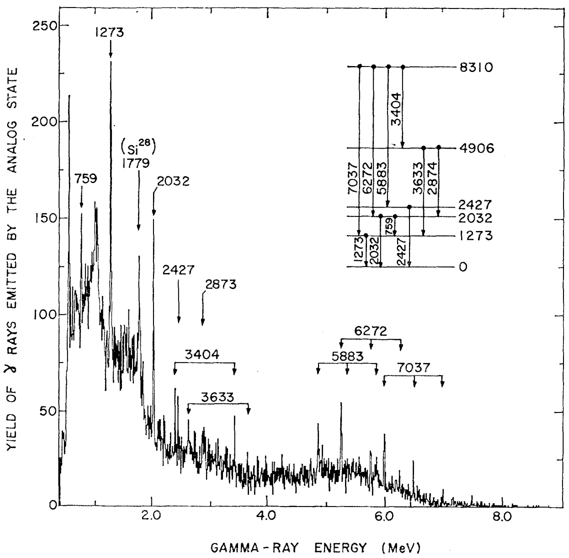

FIG. 6. γ-ray spectrum in coincidence with the protons from the $Al^{27}(He^3, p)Si^{29}$ reaction populating the analog state at 8.310 MeV. As seen by the insert, all labeled energies belong to the decay scheme of this level except for the 1.779-MeV γ ray which is produced in the (He^3, *d*) reaction. The γ rays are observed either by their photopeak or double-escape peak, depending on the energy; in some cases both these and the single-escape peak can be seen. The γ detector was located at 90° to the incident 12-MeV beam.

should agree more or less well with the intensities measured in the angular distributions at an angle of 5° and plotted in Fig. 2 and listed in Table I. The strong groups measured at low particle energies (up to about channel 480) belong to the reaction $Al^{27}(He^3, d)Si^{28}$ and will be discussed later. The pronounced (He^3, *p*) peaks labeled 37, 27, 25, 12, and 9 belong to the states in Si^{29} at 8.31, 7.085, 6.928, 5.291, and 4.903 MeV. The populations of the 1.271- and 2.026-MeV groups seem to be reduced relative to those obtained in the angular distribution measurements for the following reasons: (a) They decay directly to the ground state and thus result in one γ ray per proton while the levels at higher energies normally have a more complicated γ decay with more than one γ ray per proton—at least up to excitation energies of 8.475 MeV, the threshold for neutron decay. (b) The particle detector system was not thick enough to stop the protons leading to the low-energy levels, so the groups are smeared out and less pronounced.

The experimental data were analyzed by obtaining the γ-ray spectra in coincidence with the different proton groups populating the Si^{29} levels. Since often the proton groups overlapped heavily, great care had to be taken in selecting the limits of the proton channels over which the coincident γ rays were taken. The usual procedure was to divide the proton spectrum into a great number of intervals, usually consisting of five proton channels each. The γ spectra in coincidence with the protons in such a "slice" were extracted from the magnetic-tape record of events. By studying the change of the γ spectrum as proton slices were taken one after another, the γ decay of a state could usually be well determined even in cases in which the state was unresolved in the proton spectrum. Such a γ spectrum is shown in Fig. 6. It represents the γ decay of the analog state at 8.31 MeV. A great number of γ rays are to be seen. For low γ-ray energies, only the photopeaks are observed and labeled. For medium energies, both the photopeak and the double-escape peak are labeled; for higher energies the photopeak and the two escape peaks are labeled. All γ rays except the 1.779-MeV line are fitted into the decay scheme of the 8.3-MeV state (as indicated in the insert of Fig. 6). The 1.779-MeV line appears because of overlap (in the particle spectrum) between the peaks corresponding to the analog state and to the first excited state of Si^{28}, which is strongly excited in the $Al^{27}(He^3, d)Si^{28}$ reaction.

The yields of the γ rays were obtained by determining the area under each peak by summing the counts in the corresponding channels and subtracting a background. In some cases in which the pulse-height distributions of the γ rays overlapped, a peak-shape fitting program was used to fit the composite peak to a given number of Gaussian curves. The background under the peak was approximated either by a linear or a quadratic curve through the points on both sides of the peak or peaks of interest. In case a γ ray was represented not only by its photopeak but also by its escape peaks, the yield of each of them was determined. The intensity of a γ ray determined from the yields of its photopeak and escape peaks usually agreed to within about ±10%.

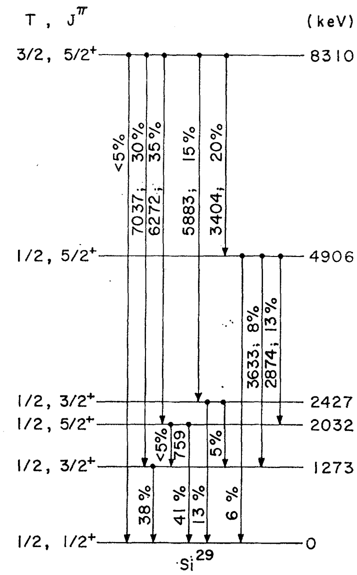

FIG. 7. Decay scheme of the analog state in Si^{29} at 8.310-MeV excitation energy. Each branching ratio is given as a percentage of the decay rate of the 8.31-MeV level. Some of these ratios, especially those of the secondary γ ray with small intensity, have relatively large errors but within our errors they agree with those known (Ref. 14) for the lower-energy states.

The branching ratios for the primary γ-ray emission can be obtained by measuring the p-γ coincidences at only one angle of the γ-ray detector relative to the incident He^3 beam. The reason is that, as mentioned earlier, the proton groups being considered are those for which $L=0$. The γ rays that follow such an unobserved primary γ ray should also be isotropic. We have obtained the branching ratio for these gammas by measuring the p-γ coincidences at three angles (45°, 90°, and 135°) and averaging these values. These numbers for the γ decay of the analog state are shown in Fig. 7, which includes the strong transitions from the analog state to the $\frac{5}{2}^+$ levels at 4.906 and 2.032 MeV and to the $\frac{3}{2}^+$ states at 2.427 and 1.273 MeV. No transition is observed to the $\frac{7}{2}^-$ state at 3.623 MeV or to the $\frac{3}{2}^-$ state at 4.935 MeV. The ground-state transition was not seen.

The results for the branching ratios can be checked by comparing the intensity of a particular primary γ ray with the sum of the intensities of the succeeding γ rays. For example, the intensity of the transition from the 8.31-MeV level to the 4.906-MeV state is 20%, while the sum of the intensities of all γ rays depopulating the 4.906-MeV level is 27%, each intensity being expressed as a percentage of all decays from the 8.31-MeV level. The discrepancy between the two numbers can be easily attributed to the relatively large error (about 50%) in the calculated decay rates of those γ rays with very small intensities and counting efficiencies. An agreement within errors is also observed between our results and the known branching ratios of the low excited states at 2.032 and 2.427 MeV.[14]

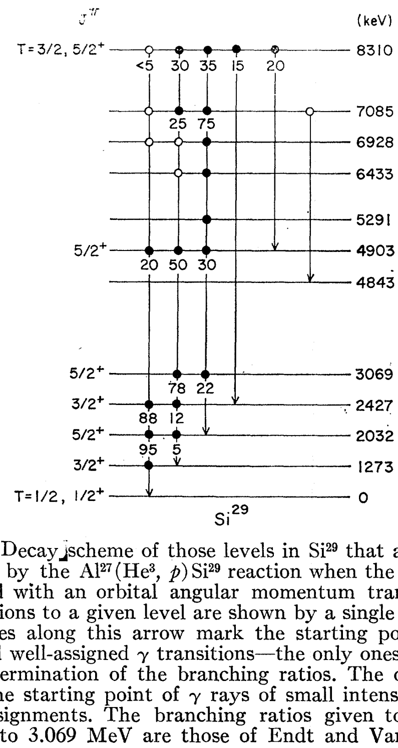

FIG. 8. Decay scheme of those levels in Si^{29} that are strongly populated by the $Al^{27}(He^3, p)Si^{29}$ reaction when the deuteron is transferred with an orbital angular momentum transfer $L=0$. All transitions to a given level are shown by a single arrow. The filled circles along this arrow mark the starting points of the strong and well-assigned γ transitions—the only ones considered in the determination of the branching ratios. The open circles indicate the starting point of γ rays of small intensities or uncertain assignments. The branching ratios given to the lower states up to 3.069 MeV are those of Endt and Van der Leun (Ref. 14).

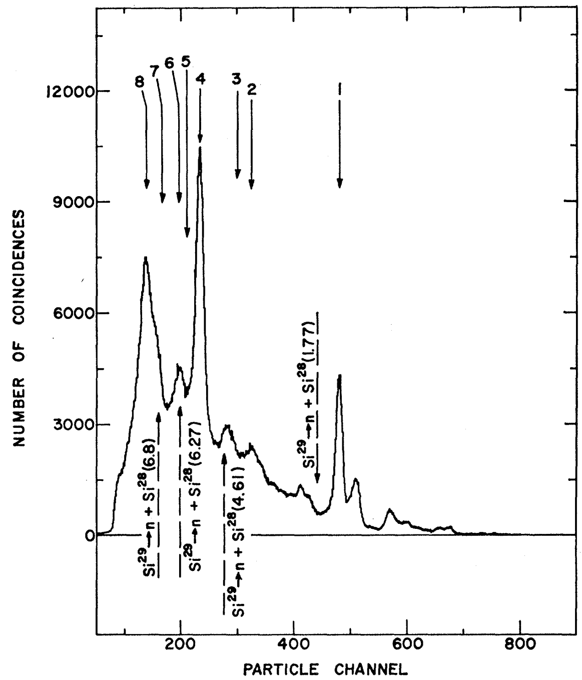

FIG. 9. Number of particles in coincidence with all γ rays. It was obtained for an Al^{27} target bombarded with a 12-MeV-He^3 beam. In contrast to Fig. 5, the arrows indicate the positions of levels in the $Al^{27}(He^3, d)Si^{28}$ reaction. They are listed with their energies in Table II. As in the (He^3, p) measurement, the particle detector was located at 0° and the γ detector at 90° to the incident beam.

The branching ratios of the states at 7.085, 6.928, 6.433, 5.291, and 4.903 MeV are shown in Fig. 8. They could be determined with only relatively poor accuracy, since these states were not as strongly excited as the analog state. Only the γ transitions whose starting points are marked by full circles are strong enough to be assigned with certainty; the doubtful and weak transitions are indicated by open circles. The branching ratios of the low excited states up to 3.096-MeV excitation energy are those of Endt and Van der Leun.[14]

The six levels at 8.31, 7.085, 6.928, 6.433, 5.291, and 4.903 MeV all show a dominant transition to the 2.032-MeV level. The three at 8.310, 7.085, and 4.903 MeV also had strong transitions to the 1.273-MeV state. Again, no negative-parity state was populated. In addition, the 4.903-MeV level has a strong γ transition to the ground state. We are certain that in this reaction this transition arises from the 4.903-MeV state and is not the 4.935-MeV γ ray previously observed.[14] As seen in column 2 of Table I, the 5° yield of this 4.935-MeV state was much less than that of the 4.903-MeV state.

2. $Al^{27}(He^3, d)Si^{28}$ Reaction

The total particle spectrum in coincidence with all γ rays is seen in Fig. 9, which shows a continuation of

TABLE II. The excitation energies E_x of the Si^{28} levels expected in the $Al^{27}(He^3, d)Si^{28}$ reaction. Arrows 6, 7, and 8 here and in Fig. 9 indicate doublets unresolvable in our experiment.

Arrow No.	1	2	3	4	5	6	7	8
E_x (MeV)	1.779	4.614	4.975	6.272	6.690	6.685 6.887	7.382 7.415	7.798 7.932

Fig. 5 to smaller particle energies. While the levels populated in the $Al^{27}(He^3, p)Si^{29}$ reaction are exhibited between channels 480 and 680 with the analog state at channel numbers around 510, the reaction $Al^{27}(He^3, d)Si^{28}$ appears in channels below 500. All levels in Si^{28} in the energy region studied are marked in Fig. 9 and are listed with their energies in Table II. In contrast to the rather meager cross section of the $Al^{27}(He^3, p)Si^{29}$ reaction, the cross sections of levels one, four, and eight in the $Al^{27}(He^3, d)Si^{28}$ process are huge. Again one would expect that an orbital angular momentum transfer $l_p=0$ is involved. Indeed, on the basis of their angular distribution measurements on the $Al^{27}(He^3, d)Si^{28}$ reaction, Hinds and Middleton[20] have concluded that these and only these levels in the studied energy region are formed by $l_p=0$ transfers. All levels marked in Fig. 9 have been analyzed in the way described in Sec. III B 1, and the resulting γ decay schemes are in good agreement with those given by Endt and Van der Leun.[14] No γ rays depopulating the levels at 4.975 and 6.69 MeV could be seen. They are both 0^+ states and obviously only poorly populated at 0°. The unlabeled resonance at channel number 280 belongs to the 5.10-MeV level in N^{14} produced by the $C^{12}(He^3, p)N^{14}$ reaction.

IV. DISCUSSION

The present results for the $Al^{27}(He^3, p)Si^{29}$ reaction are compared in Table I with previously known data on the $Si^{28}(d, p)Si^{29}$, $Si^{30}(He^3, \alpha)Si^{29}$, and $Si^{30}(d, t)Si^{29}$ reactions. In Table I, the relative strengths for populating levels in the stripping reaction are indicated by the quantity $(2J+1)\theta_n^2$, while for the pickup reactions, the strengths are given by the spectroscopic factor S. In the case of the (He^3, p) reaction, no spectroscopic factors were obtained. In this connection it is perhaps worth noting that calculated cross sections for two-nucleon transfer reactions are known to be very sensitive to small admixtures of wave functions in the nuclear states involved. Since in the present case the wave functions of Al^{27} and of the various levels of Si^{29} are not at all well known, it would be a difficult matter indeed to try to make a meaningful comparison between experimental and calculated cross sections. In Table I, the (He^3, p) yields at 5° are listed. This gives a rough measure of the relative populations of the various final states seen in Si^{29}. (A better comparison of yields might be made by taking the complete angular distributions shown in Figs. 3 and 4.)

Both the (d, t) and the (He^3, α) reactions excite the ground state $(\frac{1}{2}^+)$ and the 1.271-MeV state $(\frac{3}{2}^+)$ quite strongly. This indicates that these states carry major fractions of the $2s_{1/2}$ and $1d_{3/2}$ single-particle strengths. The states at 3.623, 4.935, and 6.387 MeV with spins $\frac{7}{2}^-$, $\frac{3}{2}^-$, and $\frac{1}{2}^-$, respectively, are strongly populated only in the (d, p) reaction and not in the pickup reactions. They may therefore be considered to have dominant $1f_{7/2}$, $1p_{3/2}$, and $1p_{1/2}$ single-particle components. All such states with large single-particle components should be only weakly excited in the $Al^{27}(He^3, p)Si^{29}$ reaction, a process which should exhibit large yields only for $L=0$ transfers forming preferentially 1h-2p states. Indeed, with the exception of the 1.271-MeV level, the above-mentioned levels are observed to be weakly excited in the (He^3, p) reaction. This particular state can, however, be formed via an $L=0$ transfer, and this may partially explain its appearance in our measurements. Since the 1.276-MeV level appears fairly strongly in all of the reactions listed in Table I, it would seem that the structure of the state is quite complex.

The states at 2.026, 4.903, and 8.310 MeV are known to have spin $\frac{5}{2}^+$ and are strongly excited in the pickup reactions but not in the (d, p) reaction. They are also strongly excited in the (He^3, p) reaction. They may therefore be considered as states reasonably well described by a configuration consisting of an inert Si^{28} core together with a $d_{5/2}$ hole coupled to an $(S=0, T=1)$ nucleon pair occupying some higher-lying shell-model level such as the $2s_{1/2}$ or $1d_{3/2}$.

There are additional states in Si^{29} which are quite strongly populated in the (He^3, p) reaction with $L=0$ but are not seen in the pickup reactions. The most notable among these are the 5.291-, 6.433-, 6.531-, 6.928-, and 7.085-MeV levels. These could also be 1h-2p states, but would have a major component formed by coupling an $S=1$ and $T=0$ nucleon pair to the $d_{5/2}$ hole. This type of configuration can, in addition to $J=\frac{5}{2}^+$, also create states with $J=\frac{3}{2}^+$ and $J=\frac{7}{2}^+$. Such configurations cannot be reached in any simple fashion by direct single-nucleon pickup reactions on a Si^{30} target. This might be especially true for the $\frac{3}{2}^+$ and $\frac{7}{2}^+$ states; for the $\frac{5}{2}^+$ states one can

[20] S. Hinds and R. Middleton, Proc. Phys. Soc. (London) **76**, 545 (1960).

easily assume a mixture of two nucleon configurations consisting of a $d_{5/2}$ hole in the Si^{28} core, in one case coupled to a nucleon pair in the singlet state and in the other to a pair in the triplet state. If this is correct, then all 1p-2h states with spin $\frac{5}{2}^+$ should be strongly excited both by the (He^3, p) reaction and by pickup reactions but the $\frac{3}{2}^+$ and $\frac{7}{2}^+$ states should be clearly seen only in the (He^3, p) reaction.

According to experience[5–7] with other nuclei in the s-d shell, one expects strong $M1$ γ-ray transitions between the analog and antianalog states in those cases in which the unpaired nucleon involved in the transition has its spin and orbital angular momenta aligned so that they add together. Thus one would anticipate a strong transition of this type in Si^{29} in which an unpaired $d_{5/2}$ nucleon is involved. In looking for candidates for the antianalog state, one must find a low-lying $J=\frac{5}{2}^+$, $T=\frac{1}{2}$ state with a configuration similar to that of the analog state. Thus the state must be strongly excited both in the (He^3, p) reaction and in the single-nucleon pickup reactions on Si^{30}, while being only weakly, if at all, excited in the $Si^{28}(d, p)$ reaction. There are two states that fulfill these requirements (the 2.026- and 4.903-MeV levels), and we indeed find that the γ decay of the analog state goes predominantly to these two states, with a 35% branch to the 2.026-MeV state and a 20% branch to the 4.903-MeV state. It is interesting to note that the γ decay does not measurably feed the 3.070-MeV level, which is also a low-lying $\frac{5}{2}^+$ level but does not satisfy the requirements listed above for the "antianalog" state.

Unfortunately the (He^3, $p\gamma$) measurements do not yield values for the absolute transition strengths for the γ decays. However, in the case of the analog state, it may not be unreasonable to assume that the total γ-ray width is about the same as that for the corresponding analog state in the mirror nucleus P^{29}. A value 0.8 ± 0.3 eV has been measured[21] for that part

TABLE III. Partial widths Γ_γ of the 8.310-MeV analog state in Si^{29}. The values were obtained by using measurements in P^{29} by Youngblood *et al.* (Ref. 18).

Transition (MeV)	E_γ (MeV)	Γ_γ (eV)	Γ_W (eV)	Γ_γ/Γ_W
8.310→4.906	3.404	0.20	0.83	0.24
8.310→2.427	5.883	0.15	4.3	0.035
8.310→2.032	6.272	0.35	5.18	0.068
8.310→1.273	7.037	0.30	7.32	0.041
8.310→0.0	8.310	<0.05	12.05	<0.004

[21] D. H. Youngblood, G. C. Morrison, and R. E. Segel, Phys. Letters **22**, 625 (1966).

of the γ ray width of the analog state in P^{29} that corresponds to decay to the four lowest particle-stable levels in P^{29}. If one adopts this value for the corresponding levels in Si^{29} and increases it to take account of the measured 20% branch to the 4.906-MeV level, one arrives at the estimate that the total γ-ray width for the 8.31-MeV analog state in Si^{29} is 1.0 ± 0.4 eV. We can now derive estimates for the partial γ ray widths Γ_γ and their ratios to the Weisskopf limits Γ_W for the different final states, as indicated in Table III. The γ-ray transition having the largest such ratio is the one leading to the $\frac{5}{2}^+$ state at 4.096 MeV. The value $\Gamma_\gamma=0.24\Gamma_W$ for this transition is comparable in magnitude to the values found for $M1$ transitions observed between isospin doublets in A^{38} and Cl^{35}. For the case of the doublets in A^{38}, Engelbertink *et al.*[22] found $\Gamma_\gamma=0.4$–$0.6\Gamma_W$; for the $\frac{7}{2}^-$ and $\frac{3}{2}^-$ isobaric spin doublets in Cl^{35}, Watson *et al.*[23] found $\Gamma_\gamma=1.6\pm0.3\Gamma_W$ and $1.0\pm0.3\Gamma_W$, respectively. In the Si^{29} case, the large value $\Gamma_\gamma=0.24\Gamma_W$ is an indication that the 4.906-MeV state is a much better candidate for the antianalog state than is the $\frac{5}{2}^+$ state at 2.032 MeV.

Recently, the γ decay of the corresponding analog state in P^{29}, the mirror nucleus, was measured.[24] Three γ transitions leading to the first, second, and third excited states were observed (as in the Si^{29} case) with branching ratios of 20, 53, and 27%, respectively. The strong transition to the $\frac{5}{2}^+$ state lying at higher energy (and corresponding to the 4.906-MeV level in Si^{29}) was not observed, but this seems to be due to experimental difficulties, namely, a high background counting rate that masks the lower-energy γ rays.

One striking feature of the measurements on the (He^3, $p\gamma$) reaction is the similarity of the γ decays for all of the 1h-2p states studied (i.e., the 8.31-, 7.085-, 6.928-, 6.433-, 5.291-, and 4.903-MeV states). They all display dominant transitions to lower states that are also strongly populated in the (He^3, p) reaction, namely states at 4.903, 2.032, and 1.273 MeV. The γ-ray transitions to the 2.425-MeV state and to the ground state were weak; the states at 3.623 MeV ($\frac{7}{2}^-$) and 3.070 MeV ($\frac{5}{2}^+$) were not measurably populated.

ACKNOWLEDGMENTS

We wish to thank Dr. Dieter Kurath and Dr. R. D. Lawson for many helpful discussions.

[22] G. A. P. Engelbertink, H. Lindeman, and M. J. N. Jacobs, Nucl. Phys. **A107**, 305 (1968).
[23] D. D. Watson, J. C. Manthuruthil, and F. D. Lee, Phys. Rev. **164**, 1399 (1967).
[24] G. C. Morrison, D. H. Youngblood, R. C. Bearse, and R. E. Segel, Phys. Rev. **174**, 1366 (1968).