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Beta Decay of Al^{29}†

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The β decay of Al^{29} has been investigated by forming the activity in the $Al^{27}(t,p)Al^{29}$ reaction at an incident triton energy of 3.1 MeV. β branches were studied by observing the subsequent Si^{29} γ-ray singles with NaI(Tl) and Ge(Li) detectors and γ-γ coincidences in two 3×3-in. NaI(Tl) detectors. In addition to the previously reported β branches to the 1273-, 2028-, and 2426-keV states in Si^{29}, a β branch to the 3069-keV level was observed. The Al^{29} β branches in percent and the corresponding $\log ft$ values for decays to the 1273-, 2028-, 2426-, and 3069-keV levels in Si^{29} were found to be 90.1 ± 1.0, 5.09 ± 0.01; 3.6 ± 0.4, 5.74 ± 0.05; 6.3 ± 0.5, 4.99 ± 0.04; and 0.027 ± 0.011, 6.16 ± 0.18, respectively. Measurements of the excitation energies of the first three excited states of Si^{29} yielded (in keV) 1273.3 ± 0.2, 2027.8 ± 0.4, and 2425.7 ± 0.4. It was also found that the 2426-keV level has a $(0.4\pm0.1)\%$ γ branch to the 2028-keV level in Si^{29}.

I. INTRODUCTION

SINCE the known spins and parities of the ground states of Al^{29} and Si^{29} are $J^\pi=\frac{5}{2}^+$ and $\frac{1}{2}^+$, respectively, Al^{29} cannot decay to the ground state of Si^{29} via an allowed transition. β decays to the first four excited states of Si^{29} are, however, allowed since the spin-parities of these levels are $J^\pi=\frac{3}{2}^+$ or $\frac{5}{2}^+$ (see, Fig. 1). Previous to this work, the β decay of Al^{29} had been studied in a number of experiments.[1] The half-life of Al^{29} had been found to be 6.52 ± 0.05 min.[1] When the present work was begun, only two of the four allowed β branches had been observed. These two branches to the 1273- and 2426-keV levels have been reported by a number of authors, the most recent at the time this work was begun being 94 and 6% branches, respectively.[2] Therefore, the major purpose of the present experiment[3] was to search for the other two allowed β branches of Al^{29} leading to the 2028- and 3069-keV states in Si^{29}. During the course of this work, Hirko *et al.*[4] reported their observation of an Al^{29} β branch to the 2028-keV level in Si^{29}.

The spectroscopic properties of the Si^{29} states below 4.0 MeV are quite well known experimentally, and there have been a number of attempts, based on the strong-coupling model[2,5,6] and the shell model,[7] to describe these states theoretically. Since the ft values for decay to the Si^{29} levels are sensitive the theoretical description of these levels, accurate measurements of the ft values for the Al^{29} β decay can furnish a check on theoretical descriptions of Si^{29}.

In the present work, we studied the β branching of Al^{29} to the first four excited states of Si^{29}, performed accurate measurements of the level energies of the first three excited states of Si^{29}, and measured the relative γ-ray branch of the 2426-keV level to the 2028-keV level in Si^{29}.

II. EXPERIMENTAL METHODS AND RESULTS

The Al^{29} activity was formed via the $Al^{27}(t,p)Al^{29}$ reaction, with a 0.3-μA beam at an incident triton energy of 3.1 MeV. The targets were 0.01-in.-thick, 99%-pure Al foil; a fresh piece of foil was used for each irradiation. The $Al^{27}(t,d)Al^{28}$ competing reaction gives rise to a 1779-keV γ ray in Si^{28}, following the Al^{28} β decay to the first excited state of Si^{28}. The $Al^{27}(t,p)Al^{29}$ reaction is prolific enough to enable us to wait at least 15 min after the beam had been taken off the target and still obtain an adequate yield of Si^{29} γ rays following the decay of Al^{29}. This allowed the 2.27-min-half-life Al^{28} activity to die off relative to the longer-lived 6.52-min Al^{29} activity. Therefore, the 1779-keV γ radiation from Si^{28} did not present a serious problem.

Following triton bombardment, the target was removed and carried to the detecting equipment located in the accelerator control room. The γ rays from the target were first studied by obtaining a series of singles spectra with a 35-cm³ Ge(Li) detector. By repeating the cycle beam on target for 20 min, wait 20 min, count 30 min, and summing three such spectra, statistical accuracy sufficient to establish the observed γ-ray energies to about ±1 keV was obtained. This enabled us tentatively to identify the γ rays from the decay of the 1273- and 2028-keV levels and the two major branches of the 2426-keV level in Si^{29}. Identification of these γ rays was made firm by obtaining three successive spectra of 10-min duration, each beginning at 30, 40, and 50 min after the beam was taken off the target. In this way, we established that the intensities of the γ rays assigned to Si^{29} were, in fact, decaying at the same rate, and that this rate corresponded to a half-life of about 6.5 min. Aside from the Si^{28} 1779-keV γ ray, the only contaminant γ ray observed was annihilation radiation resulting from the positron decay of F^{18}. This

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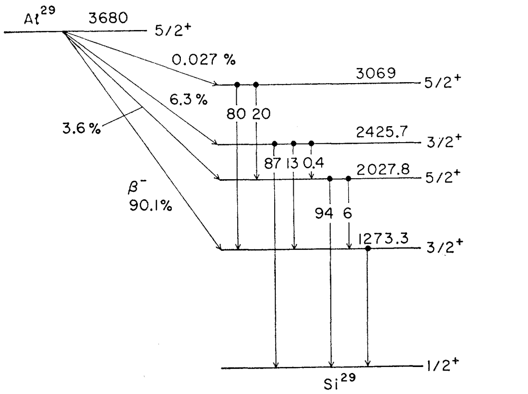

FIG. 1. Proposed decay scheme of Al^{29}. The β branches of Al^{29} to the first four excited states of Si^{29}, the excitation energies of the first three excited states of Si^{29}, and the γ-ray branching ratio of the 2426-keV level to the 2028-keV level in Si^{29} are from the present experiment. All other γ-ray branching ratios (in %) were taken from Ref. 8.

activity is produced in the surface oxide by the $O^{16}(t, n)F^{18}$ reaction.

Having identified the observed γ rays that originate from the first three excited states of Si^{29}, the relative β branches to these states were deduced from the γ-ray intensities, the known γ-ray branching ratios of the first three excited states of Si^{29},[8] and the relative γ-ray efficiencies of the Ge(Li) detector. In order to minimize the uncertainty in the β-branching intensities to the first three excited states due to the uncertainty in the Ge(Li) efficiencies, the relative β branches were also determined from γ-ray singles measurements, using a 3×3-in. NaI(Tl) detector.

It was not possible to identify the 1796-keV γ ray, following β feeding of the 3069-keV state in Si^{29}, in the γ-ray singles spectra (described above) taken with Ge(Li) or NaI(Tl) detectors. This indicated a β branch to the 3069-keV level that was weak enough to make impractical a search for the 1796-keV γ ray with the Ge(Li) detector. The proximity of the Si^{28} 1779-keV γ ray ruled out a search for the 1796-keV γ ray using a NaI(Tl) detector. Therefore, two 3×3-in. NaI(Tl) detectors were used to study all γ rays that were in coincidence with the 1273.3-keV γ ray. The resulting coincident spectrum is shown in Fig. 2. These data represent the sum of 18 15-min runs, each started at least 30 min after the end of the bombardment of the target. From the intensity ratio of the 1796-keV to the 1153- and 755-keV γ rays, the γ-ray branching ratios from Ref. 8, and the known relative efficiencies of the 3×3-in. NaI(Tl) detector, the relative β branch to the 3069-keV level was established. The NaI(Tl) detector would not, of course, resolve the weak 1796-keV γ radiation from any 1779-keV randoms from Si^{28}. It is therefore necessary to estimate the extent to which the 1779-keV random γ rays could contribute to the peak at 1796 keV. From one of the Ge(Li) singles spectra, we could establish an upper limit for the ratio of the Si^{28} 1779-keV γ-ray intensity to the Al^{29} 2028-keV γ-ray intensity. Since the period between bombardment of the target and γ-ray detection was at least 10 min longer for the coincidence runs than for the Ge(Li) singles run that was considered, this upper limit, corrected for the difference in relative efficiencies of the detectors, could be applied to the coincidence data. Based on the intensity of the random peak from the 2028-keV γ ray, an upper limit of 3% can be placed on the random contribution by Al^{28} 1779-keV γ radiation to the peak at 1796 keV. This upper limit corresponds to approximately $\frac{1}{10}$ of the quoted uncertainty in the β branch to the 3069-keV level. The Al^{29} β branches, and corresponding log*ft* values, are summarized in Table I.

A high-resolution (2 keV full width at half-maximum for the 1332.5-keV Co^{60} line) 10-cm^3 Ge(Li) detector was used to measure accurately the level energies for the first three excited states of Si^{29}.[9] By comparing the 1273-keV Si^{29} γ ray with the 1173.23±0.04- and 1332.49±0.04-keV γ rays from Co^{60}, and the unresolved 1274.55±0.04-keV γ ray from Na^{22}, we obtained a level energy of 1273.3±0.2 keV for the first excited state of Si^{29}. Comparison of the 2028-keV Si^{29} γ ray with the one-escape peak of the 2614.47±0.10-keV line from Th*C''* and of the 755-keV cascade γ ray from the Si^{29} 2028-keV level with the 661.635±0.076- and 834.81±

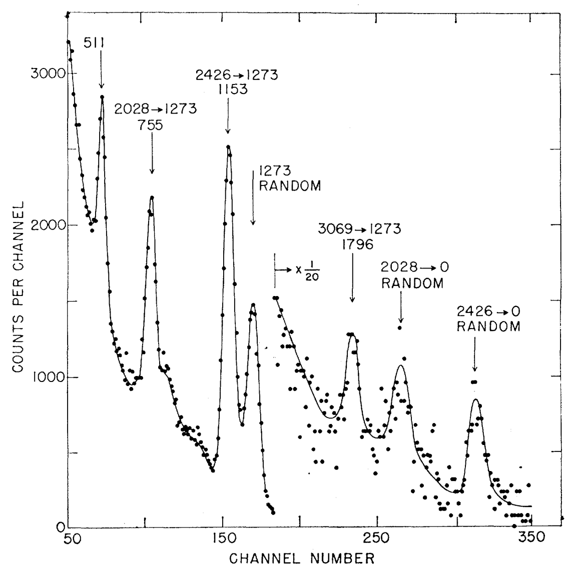

FIG. 2. Al^{29} γ-ray spectrum in a 3×3-in. NaI (Tl) detector in coincidence with another 3×3-in. NaI(Tl) detector when a pulse-height channel was imposed on the 1273-(keV γ-ray peak in the output of the latter detector.

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[9] Energies quoted for the standards were taken from J. B. Marion [University of Maryland Technical Report No. 656, 1968 (unpublished)], except for the Ba^{133} γ rays, which are from A. Schwarzschild (private communication).

0.03-keV γ rays from Cs^{137} and Mn^{54}, respectively, led to a level energy 2027.8±0.4 keV for the second excited state of Si^{29}. This result is confirmed by a comparison of the 755-keV cascade from this level with the one-escape peak of the 1273-keV Si^{29} γ ray. Comparison of the photopeak of the 2426-keV Si^{29} γ ray with the ThC'' line and the 2426-keV second-escape peak with the 1332.5-keV line in Co^{60} led to a level energy of 2425.7±0.4 keV for the third excited state of Si^{29}. The level energies given in Fig. 1 and Table I for the first three excited states are based on these measurements, while the level energy quoted for the fourth excited state is from Ref. 1.

All of the γ-ray branching ratios shown in Fig. 1 are taken from Ref. 8, with the exception of the weak branch of the 2426-keV level to the 2028-keV level. Becker *et al.*[8] were able to establish an upper limit of 3% for this branch, while a 398-keV γ ray was actually observed in the present experiment. We established in two ways that this 398-keV γ ray did, in fact, correspond to the transition from the 2426-keV level to the 2028-keV level of Si^{29}. First, using the high-resolution Ge(Li) detector, its energy, measured by comparison with the known γ rays in Ba^{133},[9] was found to be 397.8±0.3 keV, which agrees well with the transition energy of 397.9±0.6 keV expected on the basis of our determination of the level energies for the second and third excited states of Si^{29}. As a second check on the origin of the 398-keV γ ray, we accumulated two separate spectra; one starting 15 min after the triton bombardment and lasting 10 min, and a second immediately following the first. The sum of 14 such spectra yielded statistical accuracy sufficient to establish that the intensity of this 398-keV γ ray decayed at the same rate as the 1153- and 755-keV γ rays. This, together with the accurate energy measurement, established the 398-keV γ ray as the cascade from the 2426-keV level to the 2028-keV level. The relative γ-ray branch of the 2426-keV level to the 2028-keV level is (0.4±0.1)%.

III. DISCUSSION

The logft values of 5.09, 5.74, and 4.99, which were measured in the present experiment for the Al^{29} β decay to the first three excited states of Si^{29}, respectively, are in good agreement with the corresponding values of 5.0, 5.7, and 4.9 reported by Hirko *et al.*,[4] and our logft value of 6.16 for the β decay to the 3069-keV level in Si^{29} is consistent with their lower limit of 5.1. Our β branches to the first three excited states also agree, within the experimental uncertainties, with recent measurements made by Jones *et al.*,[10] given in column 2 of Table I, and our value of 0.027% for the relative branch to the 3069-keV level is consistent with their upper limit of 0.1%.

TABLE I. Summary of the experimental information on the β decay of Al^{29}.

Si^{29} level energy (keV)	β branch (%) Ref. 10	Present work	logft value (present work)
1273.3±0.2[a]	89.1±0.7	90.1±1.0	5.09±0.01
2027.8±0.4[a]	4.1±0.3	3.6±0.4	5.74±0.05
2425.7±0.4[a]	6.8±0.5	6.3±0.5	4.99±0.04
3069[b]	≤0.1	0.027±0.011	6.16±0.18

[a] Present work.
[b] Reference 1.

TABLE II. Comparison of experimental and theoretical relative β moments. The experimental values are from the present work and the theoretical values assume a strong-coupling model for Al^{29} and Si^{29}, taking $K=\frac{5}{2}$ for Al^{29} and assuming the model given in Ref. 5 for Si^{29}.

Level in Si^{29} (keV)	Relative β moment (theoret)	Relative $(ft)^{-1}$ (expt)
1273.3	0.81	0.81±0.02
2027.8	0.03	0.18±0.02
2425.7	0.28	1.02±0.18
3069	0.43	0.07±0.02

The level energy for the first excited state of Si^{29} from the present work is the same as that quoted in Ref. 1. Our values of the energies of the second and third excited states are, however, 3.9 and 1.4 keV, respectively, lower than those quoted in Ref. 1. The value of (0.4±0.1)% for the relative γ-ray branch of the 2426-keV level to the 2028-keV level is consistent with the upper limit of 3% quoted in Ref. 8.

The logft values for the Al^{29} β decay to the first four excited states of Si^{29} are all consistent with these transitions being allowed. The allowed nature of these transitions is, in turn, consistent with the known spins and parities of the first four excited states of Si^{29},[1] and of the ground state of Al^{29}.[11]

In a more quantitative fashion, the results of the present experiment can be compared with theoretical descriptions of Si^{29} and of the ground state of Al^{29}. In particular, the ratios of the experimental $(ft)^{-1}$ values from the present work can be compared to the β moments predicted by the strong-coupling model of Ref. 5. Ejiri[5] has described the low-lying positive-parity states of P^{29}, taking into account the $K=\frac{3}{2}$ Nilsson orbit 8, and the $K=\frac{1}{2}$ Nilsson orbits 9 and 11. Since P^{29} is the mirror nucleus of Si^{29}, we have taken Ejiri's[5] description of the first four excited states of P^{29} to describe the first four excited states of Si^{29}. The ground state of Al^{29} is known to have $J^\pi=\frac{5}{2}+$,[11] and the prolate shape with $K=\frac{5}{2}$ seems definitely to be preferred for Al^{29}.[2,12] With the assumption that $J=K=\frac{5}{2}$ for the ground state of Al^{29}, and assuming Ejiri's strong-coupling description for the first four excited states of Si^{29} $(K\leq\frac{3}{2})$, the Fermi moment vanishes and the Gamow-

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Teller moment is K-forbidden ($\Delta K>1$) for the $K=\frac{1}{2}$ parts of a given Si^{29} state. If it is assumed that the two neutrons outside the Si^{28} core are in either Nilsson orbits 9 or 11 for the Al^{29} ground state, the single-particle nature of the β-decay operator would forbid a transition to Ejiri's $K=\frac{3}{2}$ components of the Si^{29} levels as well. Thus, this restriction on the Al^{29} ground state, with Ejiri's description for the Si^{29} states, requires that the β moments vanish and disagrees, therefore, with the experimentally observed allowed nature of the decays to the first four excited states of Si^{29}. Thus, if Ejiri's description of Si^{29} is to lead to nonzero β moments, it is necessary to assume a component of the Al^{29} ground state in which these two extra core neutrons are in Nilsson orbit 8. Under these conditions, the strong-coupling model predicts that the ratio of the β moment for the β decay of Al^{29} to state 1 to that for the decay to state 2 in Si^{29} is

$$\frac{|A_{3/2}^{(1)}|^2(\frac{5}{2}\,\frac{5}{2}\,1\,-1\mid J^{(1)}\tfrac{3}{2})^2}{|A_{3/2}^{(2)}|^2(\frac{5}{2}\,\frac{5}{2}\,1\,-1\mid J^{(2)}\tfrac{3}{2})^2},$$

where $(\frac{5}{2}\,\frac{5}{2}\,1\,-1\mid J^{(1)}\frac{3}{2})$ is a vector-addition coefficient, $J^{(1)}$ is the spin of state 1, and $A_{3/2}^{(1)}$ is the amplitude of the $K=\frac{3}{2}$ part of the wave function for state 1. Experimentally, the corresponding ratio of β moments is given by

$$[(ft)_1]^{-1}/[(ft)_2]^{-1}.$$

In Table II, the relative β moments, using the $K=\frac{3}{2}$ amplitudes from Ref. 5, are compared with the relative values of $(ft)^{-1}$ from the present experiment for the first four excited states of Si^{29}. The theoretical values have been normalized to the experimental values for the transition to the 1273-keV level. In general, the agreement is very bad. The theoretical and experimental values of the β moment for the 2028-keV level relative to the 2426-keV level agree at least qualitatively. The theory, however, predicts the β moments for the 2028- and 2426-keV levels to be much too low, relative to that for the 1273-keV level; and the theoretical moment for decays to the 3069-keV level is much too high, relative to those for decays to the other three states. Therefore, if it is assumed that $K=\frac{5}{2}$ for Al^{29}, the β-decay results in the present experiment are in direct disagreement with the strong-coupling description of P^{29} given in Ref. 5. A possible explanation for the bad agreement between the theoretical prediction and experimental results for the β decay that would preserve the strong-coupling picture for P^{29} (and therefore for Si^{29}) given in Ref. 5 is that the ground state of Al^{29} is not pure $K=\frac{5}{2}$. If the ground state of Al^{29} were described by $K=\frac{1}{2}$ or $\frac{3}{2}$ (or by admixtures of $K=\frac{1}{2}$ and/or $\frac{3}{2}$ with $K=\frac{5}{2}$), the theoretical relative β moments could be drastically different than those appearing in Table II.

It would be interesting to compare these β-decay results with a shell-model description of the levels involved. Unfortunately, we could find detailed shell-model calculations neither for the Al^{29} ground state, nor for the first four excited states of Si^{29}. Taking the 1273-keV level in Si^{29} as a $d_{3/2}$ neutron outside of the closed $d_{5/2}$ shell is consistent with the relatively large spectroscopic factor for stripping to this level in the $Si^{28}(d,p)Si^{29}$ reaction[13] and the inhibited speed of the 1273-keV γ ray.[14] A reasonable shell-model description of the Al^{29} ground state would be a $d_{5/2}$ proton hole with two neutrons in the $2s_{1/2}$ or $1d_{3/2}$ shell, whose angular momenta couple to zero;

$$|Al^{29}\rangle^{5/2}=a[\pi_{5/2}^{-1}(\nu_{3/2}^{2})^0]^{5/2}+(1-a^2)^{1/2}[\pi_{5/2}^{-1}(\nu_{1/2}^{2})^0]^{5/2},$$

where π denotes a proton and ν a neutron. If this configuration is assumed for the Al^{29} ground state, and the first excited state of Si^{29} is taken to be the $d_{3/2}$ single-particle state, only the $[\pi_{5/2}^{-1}(\nu_{3/2}^{2})^0]^{5/2}$ part of the assumed Al^{29} ground state contributes to the allowed Gamow-Teller decay to the first excited state of Si^{29}. If a is taken to be unity, the predicted $\log ft$ is 3.74. Therefore, the measured $\log ft$ of 5.09 leads to a predicted value of a^2 of 4.5%, which seems quite reasonable, since the $2s_{1/2}$ single-particle level is expected to be somewhat lower in energy than the $1d_{3/2}$ single-particle level in the shell-model picture.[7] Hence, the $\log ft$ value for decay to the 1273-keV level in Si^{29} measured in the present experiment is not inconsistent with a simple shell-model picture for the ground state of Al^{29} and for the first excited state of Si^{29} without a detailed shell-model calculation. Similar estimates of the $\log ft$ values for the decays to the higher states in Si^{29} would be unrealistic, since these states are certainly not simple single-particle states.

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