Kurath[8] in their study of the complete p-shell and by Barker[9] in his study of the lithium and beryllium nuclei, as shown in Table VI. The excellent agreement between the measured value of the lifetime ratio and that predicted for strong L-S coupling is especially satisfying. The earlier and much larger experimental value of the ratio had raised doubts[2,19] as to the validity of calculations which neglect the motion of the core in these nuclei.

ACKNOWLEDGMENTS

We would like to thank G. D. Sprouse for his generous assistance and interest in this work. We are grateful to L. G. Mann, D. C. Camp, and G. A. Armantrout of the Lawrence Radiation Laboratory, Livermore, for making available to us the large Ge(Li) detector used in part of the work. We would also like to thank P. R. Bevington for his advice in the use of the PDP-7 computer.

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Beta-Delayed Protons from Si^{25}†

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Silicon-25 was produced by the $Mg^{24}(He^3,2n)Si^{25}$ reaction with a 32-MeV He^3 beam. The beta-delayed proton spectrum was measured from 0.7 to 6.0 MeV, with a resolution of 85 keV full width at half-maximum above 1.7 MeV. Eighteen proton peaks are identified and assigned to transitions from virtual levels of Al^{25}. Three new levels of Al^{25} at 6.92±0.04, 7.25±0.03, and 8.20±0.03-MeV excitation energy are proposed in addition to the $T=\frac{3}{2}$ analog state at 7.90±0.02 MeV and a state at 8.97±0.04 MeV which had been seen in previous delayed-proton work. The Si^{25} half-life was determined to be 218±4 msec.

INTRODUCTION

Silicon-25 was one of the first isotopes reported to decay by beta-delayed proton emission.[1] Among the light elements a series of nuclides ranging from C^9 to Ti^{41} have also been shown to exhibit this mode of decay.[2] These nuclides have beta-decay half-lives less than 0.3 sec. They are produced by nuclear reactions using pulsed beams and the proton spectra are observed between beam pulses with solid-state detectors. In the case of Si^{25}, allowed beta transitions populate states of Al^{25} which then emit protons if the excitation energy of the state is greater than the proton separation energy of Al^{25} which is 2.29 MeV. Because the first excited state in the final nuclide Mg^{24} is only 1.37 MeV above the ground state, proton emission from higher excited states of Al^{25} may go to either the ground or first-excited state. Thus the proton spectrum may be doubled relative to the number of states populated by beta decay. McPherson and Hardy[3] measured the half-life of Si^{25} to be 225±6 msec and reported at least four and possibly six groups in the proton spectrum. They assigned two of their proton peaks to a known level in Al^{25} at 7.14 MeV and two other proton peaks to a new level at 7.93 MeV. The new level was assumed to be the analog state of the ground state of Si^{25} since the $\log ft$ for the beta transition was significantly less than the $\log ft$ for the 7.14-MeV level. Similar analog-state peaks have now been seen in most of the other beta-delayed proton spectra.[4] Later results of Hardy and Bell for Si^{25} put the new level at 7.91 MeV and suggested that two more peaks were present arising from transitions from a proposed level at 9.03 MeV.[5] Delayed protons from Si^{25} have also been observed by Bender, Williams, and Toth.[6]

The level structure of Al^{25} has been studied by proton elastic and inelastic scattering on Mg^{24}, and many levels have been found above the proton separation energy.[7] In the more extensively studied mirror nucleus, Mg^{25}, sixty levels have been seen in this region.[8] If some of these levels are populated by allowed beta decay, the delayed-proton spectrum should be far more complex than has been previously reported. We have measured the delayed-proton spectrum of Si^{25} with a resolution

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[1] R. Barton, R. McPherson, R. E. Bell, W. R. Frisken, W. T. Link, and R. B. Moore, Can. J. Phys. **41**, 2007 (1963).
[2] R. McPherson, R. A. Esterlund, A. M. Poskanzer, and P. L. Reeder, Phys. Rev. **140**, B1513 (1965), and references therein.
[3] R. McPherson and J. C. Hardy, Can. J. Phys. **43**, 1 (1965).
[4] J. C. Hardy and B. Margolis, Phys. Letters **15**, 276 (1965).
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[6] R. S. Bender, I. R. Williams, and K. S. Toth, Nucl. Instr. Methods **40**, 241 (1966).
[7] Data for Al^{25} have been taken primarily from P. M. Endt and C. Van der Leun, Nucl. Phys. **34**, 1 (1962) with additions from T. Lauritsen and F. Ajzenberg-Selove, *Energy Levels of Light Nuclei* (National Academy of Science–National Research Council, Washington, D. C., 1962), and corrections from W. T. Joyner, Phys. Rev. **128**, 2261 (1962).
[8] R. K. Sheline and R. A. Harlan, Nucl. Phys. **29**, 177 (1962).

of about 85 keV and have extended the observations to lower proton energies.

EXPERIMENTAL

Silicon-25 was produced at the Brookhaven 60-in. cyclotron by the (He^3,$2n$) reaction[9] on Mg^{24}. The threshold for this reaction was estimated to be 21 MeV. The He^3 energy was 32 MeV and continuous external beam currents of about 0.1–0.2 μA were available. The external beam was pulsed, however, by means of a mechanical chopper which intercepted the beam with a gold foil 0.01 in. thick. Before entering the target chamber the beam was collimated to a $\frac{1}{8}$-in.-diam circle. Six inches downstream from this opening was a $\frac{3}{16}$-in.-diam antiscattering collimator. The target chamber was a 17-in.-diam aluminum-walled cylinder 6 in. deep with brass bottom and Lucite top. The beam intensity was monitored using a Faraday cup which consisted of a 6-in.-long by 1.5-in.-diam aluminum cylinder with a gold foil as beam stopper. The Faraday cup was recessed in the exit port of the target chamber and was connected to an integrating electrometer.

The spectra presented here were obtained with unbacked Mg targets, 0.59 mg/cm^2 thick, which were supported on aluminum frames $\frac{3}{8}$ in. high by 3 in. wide. It had been determined that aluminum targets did not yield any delayed proton activity. In order to increase the yield without increasing the target thickness in the counter direction, the plane of a target was placed at a 10-deg angle to the beam.

Delayed protons were detected by 3-cm^2 surface-barrier silicon detectors of nominal 500-μ depletion depth. A detector was mounted facing the plane of the target at a distance of 1.5 in. The best resolution over most of the proton spectrum was obtained at a bias of 40 V with a detector of 6400-Ω cm resistivity. With each beam pulse, the leakage current through the detector pulsed by several microamperes depending on the beam intensity and detector geometry. This effect was greatly reduced by placing bar magnets near the target. A transistorized, charge-sensitive preamplifier was connected to the detector via a short (<8 in.) coaxial cable and a vacuum-tight connector in the bottom of the chamber.

Pulses from the preamplifier were amplified and shaped by double delay-line clipping (0.7 μsec). The pulse-height spectrum was presented to the analog-to-digital converter of a 4096-channel multiparameter analyzer, to a pulse-shape discriminator, and a pulse-height discriminator. The discriminators were used in coincidence to gate the analyzer and served, respectively, to reject analysis of overlapping pulses and to reject low-energy pulses generated by the large number of beta particles entering the detector. An energy-calibration signal from a pulse generator was inserted at the detector and was used to set the energy scale of the analyzer, to determine the electronic resolution and to check for long-term calibration changes.

A repetitive sequence of a 0.5-sec beam burst followed by a 0.8-sec counting period was controlled by an oscillator and interval timer. Pulses from the timer operated the beam chopper and turned the analyzer on and off. An accurate time-base generator was started at the end of each beam burst and was used for external control of the address register of the analyzer. In this manner, proton energy spectra were recorded as a function of time after end of bombardment. The spectrum shown in Fig. 1 is the result of the analysis of eight successive spectra each of 256 energy channels taken after each beam burst. The time interval for each spectrum was 100 msec so that data were recorded for almost four half-lives of the Si^{25} decay. With a single detector at 40-V bias, this system allowed observation of the proton spectrum down to an energy of 1.7 MeV. The spectrum of Fig. 1 required 20 hr for accumulation.

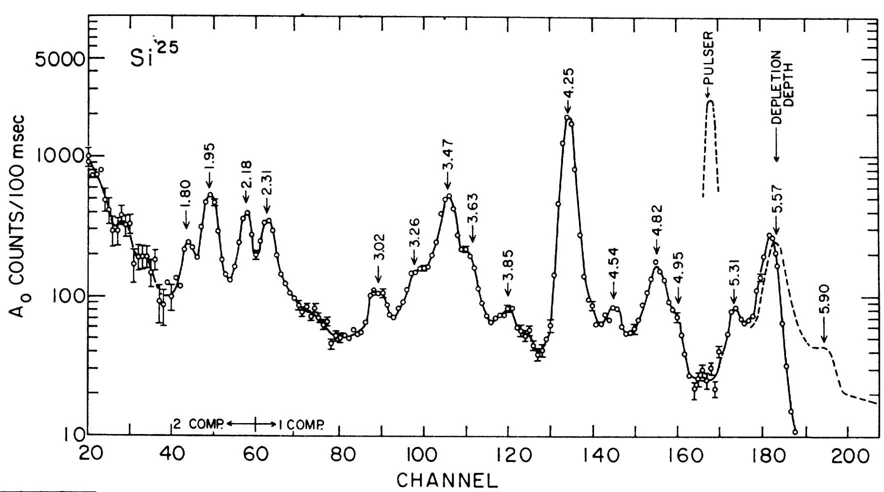

FIG. 1. Spectrum of beta-delayed protons from Si^{25}. One detector was used at 40 V bias. The dashed curve at high energy has been drawn from data taken at 100 V bias. The pulser peak indicates the electronic resolution. Energies are $E_{c.m.}$ in MeV. The points plotted are the initial activities of the 218-msec component of eight point decay curves. Below channel 60 a second long-lived component was used to fit the background.

[9] P. L. Reeder, A. M. Poskanzer, and R. A. Esterlund, Phys. Rev. Letters 13, 767 (1964).

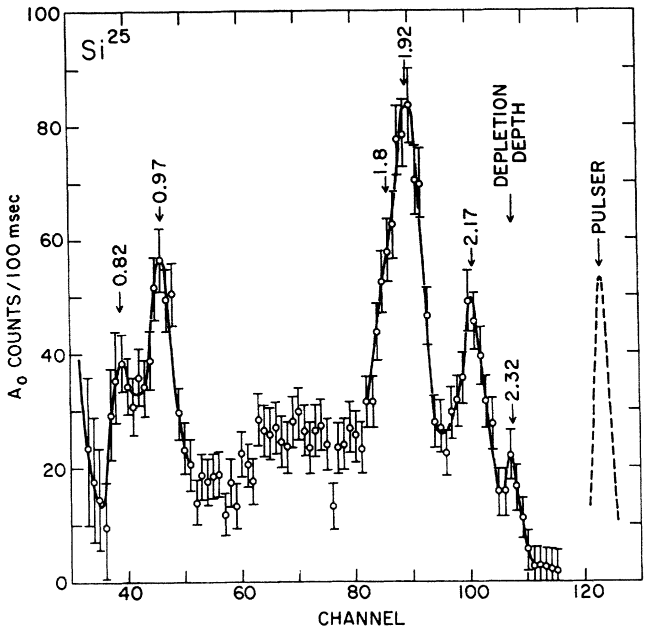

FIG. 2. Low-energy delayed-proton spectrum obtained with thin transmission detector. Energies are $E_{c.m.}$ in MeV.

The difficulty in observing lower energy protons was due to the interference from multiply scattered beta particles in the thick detector. This effect was greatly reduced by using a thin (65-μ) transmission counter of 1.5 cm^2 area to stop protons up to 2.1 MeV in energy. A thick anticoincidence detector behind the transmission detector was used to eliminate those peaks due to higher energy protons which passed through the thin detector. To insure that all protons passing through the transmission detector entered the anticoincidence detector, a Venetian-blind collimator consisting of vertical $\frac{1}{4}$-in.-wide strips of 0.001-in. aluminum spaced by 0.1 in. was placed between the target and the transmission detector. For low-energy observations, the analyzer memory was divided into four quarters of 1024 channels each. Each quarter operated as a 128-energy by 8-time-channel analyzer. A multiple-coincidence circuit and routing logic directed storage of signal pulses in the various quarters. One quarter stored the events which passed an energy discriminator and a pulse-shape discriminator and were not accompanied by a pulse in the anticoincidence detector. Pulses rejected by the pulse-shape discriminator were stored in another quarter. A third quarter stored the spectrum of pulses from the thin detector but gated by a coincidence between the two detectors. This provided the through-peak spectrum of the thin detector. A calibration spectrum could be stored in the fourth quarter. This system allowed examination of the proton spectrum from 0.7 MeV up to 2.1 MeV, and the results are shown in Fig. 2.

The energy scales were calibrated by taking a series of pulser settings with the cyclotron beam and electronics operating as during a normal experiment. These pulser settings were then calibrated with three alpha sources, Am^{241}(5.48 MeV), Cm^{244} (5.80 MeV) and Pb^{212} (8.78 MeV) without the cyclotron beam. By taking alpha spectra at two angles to the counter, a 20-keV dead layer was found for the surface barrier detectors. This correction was taken into account for the alpha calibration but no dead-layer correction was made for the protons.

RESULTS

The contents of the analyzer memory were read out digitally on punched paper tape which was then converted to magnetic tape. A least-squares fitting program[10] was modified to accept these data from magnetic tape.

Our best determination of the half-life of Si^{25} resulted from an analysis of the coincidence counts from the telescope described above which was used to obtain the through-peak spectrum of the thin detector. This coincidence method is expected to have the least amount of background contributions from beta and alpha particles. A one-component fit to the data yielded 218±4 msec. In three other experiments, when the singles spectra were summed over energy and analyzed with the addition of a second component, a long-lived background, the half-lives were statistically consistent with this value although the errors were larger. Also, when the counts under each major peak in an energy spectrum were summed and then analyzed with a 218-msec half-life, the goodness-of-fit parameters which were obtained were statistically reasonable, indicating

[10] J. B. Cumming, in *Application of Computers to Nuclear and Radiochemistry*, edited by G. D. O'Kelley (Office of Technical Services, Washington, D. C., 1963), NAS-NS 3107.

TABLE I. Energies and intensities of delayed-proton peaks.

$E_{c.m.}$ (MeV)	Relative intensity[a]	$E_{c.m.}$ (MeV)	Relative intensity[a]
0.82±0.05	14	3.63±0.04	11
0.97±0.05	23	3.85±0.03	8
1.80±0.03	11	4.25±0.02	100
1.95±0.03	40	4.54±0.03	7
2.18±0.03	24	4.82±0.03	17
2.31±0.03	25	4.95±0.05	2
3.02±0.03	10	5.31±0.03	6
3.26±0.04	15	5.57±0.04	20
3.47±0.03	39	5.90±0.05	2

[a] Relative to 100 for the most intense peak at 4.25 MeV.

that the decay of each of the peaks was consistent with this half life.

To obtain the Si^{25} energy spectrum free from background, each energy channel of the original data was then analyzed with one component or, in the case of the lower energy channels, two components of fixed half life. The initial activity of the 218-msec component was then plotted versus channel number to obtain the energy spectrum shown in Fig. 1. The widths of the peaks can be accounted for by the target thickness and the instrumental resolution indicated by the pulser peak. For the low-energy experiment a two-component analysis gave poor results for the energy spectrum. However, a smoothed background based on the two-component analysis was subtracted from the original data and a one-component fit gave the spectrum shown in Fig. 2. Many proton peaks may exist in the region from 1.0 to 1.7 MeV, but since our resolution and statistics were not sufficient to distinguish them, we have not attempted to interpret this region. However, from the data in Fig. 2, we estimate that any peak in this region has an intensity less than 7% of the main peak at 4.25 MeV.

Because of the target thickness, alpha particles would give much broader peaks than those observed. Therefore we have ascribed all the structure in the two spectra to proton groups originating from levels of Al^{25}. The peak positions were converted to observed energies using the calibration data. Each energy was then corrected for the energy lost in passing through half the target thickness using the range-energy tables of Williamson and Boujot.[11] A recoil correction was then applied to give the proton decay energy (labeled $E_{c.m.}$). The relative intensity for each peak was determined by integrating the initial-activity spectrum with the assumption that each peak had a symmetrical shape. The intensities of peaks in the low-energy spectrum (Fig. 2) were normalized to the sum of the intensities of the peaks at 1.80 and 1.95 MeV which appeared in both spectra. Table I lists the proton-decay energies for the observed peaks and their intensities relative to 100 for the most intense peak. The uncertainty in energy is our estimate of the expected error, based on the error in calibration and the error in determining the peak position.

[11] C. Williamson and J. P. Boujot, Commissariat à l'Energie Atomique Report No. 2189, 1962 (unpublished).

PROPOSED DECAY SCHEME

Most of the Al^{25} levels observable in this experiment can decay by proton emission to more than one final state in Mg^{24}. This complicates the assignment of proton peaks to transitions between levels in Al^{25} and Mg^{24}. Any decay scheme proposed on the basis of fitting transition energies and intensities alone must be considered as tentative since the assignments can only be verified by coincidence experiments. However, a decay scheme for Si^{25} can be constructed which is consistent with all our observations. Ambiguities in assignments will be pointed out where they occur.

Each observed proton decay energy plus the proton separation energy of Al^{25} (2.287±0.007 MeV) plus the excitation energy of the final state (0.0, 1.37, or 4.12 MeV for the 0+ ground, 2+ first excited, or 4+ second excited state of Mg^{24}) allows assignment of the proton peak to a level in Al^{25}. Since these levels are most likely populated by allowed beta transitions, they presumably have $J=\frac{3}{2}$, $\frac{5}{2}$, or $\frac{7}{2}$ and positive parity. This is based on the assumption that Si^{25} has the same spin-parity as its mirror nucleus Na^{25} which is $\frac{5}{2}+$. The branching ratios for proton transitions from these $\frac{3}{2}+$, $\frac{5}{2}+$, or $\frac{7}{2}+$ levels to the 0+, 2+, or 4+ states in Mg^{24} are expected to be dependent upon the spin change. For example, for these Al^{25} states the angular-momentum barrier favors the emission of protons to the 2+ state over the 0+. Optical-model transmission coefficients were calculated for protons incident on states of Mg^{24}. Ignoring nuclear-structure effects, the transmission coefficients allow a qualitative prediction of these branching ratios and are used in certain cases to aid in the analysis.

From the energies listed in Table I proton peaks are found which fit transitions from eight previously observed levels in Al^{25}. Two of these levels had been recently assigned from delayed-proton work.[3,5] The remaining proton peaks suggest three new levels. These assignments are summarized in Table II. The first column lists the levels of Al^{25} from which protons are observed.[7] Where known, the spins and parities of these levels are given in column 2. Since these levels are populated by allowed beta decay, the 6.15-MeV level must be $\frac{3}{2}+$ rather than $\frac{1}{2}+$. The level at 7.90 MeV is the analog state to the Si^{25} ground state and is therefore $T=\frac{3}{2}$, $J=\frac{5}{2}+$. The second excited state in Na^{25} occurs at 1.07 MeV[7] and thus there should be a $T=\frac{3}{2}$ state in Al^{25} at approximately 8.97 MeV where we observe our highest energy level. That this state could have $T=\frac{3}{2}$ was pointed out by Hardy and Bell[5] on the basis of slightly different energies.

The third column of Table II gives the predicted

TABLE II. Summary of the decay scheme of Si^{25}.

Level in Al^{25} (MeV)	Known $J\pi$	Expected proton energy[a] $E_{c.m.}$ (MeV)	Experimental proton energy[a] $E_{c.m.}$ (MeV)	Relative proton intensity[b]	Relative beta intensity[c]	$\log ft$[d]
3.88	$\frac{5}{2}+$	1.59		<7	<6	>6.1
4.22	$\frac{3}{2}+$	1.93	1.95±0.03	40	≳33	≲5.3
		0.56		e		
4.59	$\frac{5}{2}+$	2.30	2.31±0.03	25	40	5.1
		0.93	0.97±0.05	23		
5.81		3.52		f	>20	<5.0[f]
		2.15	2.18±0.03	24		
6.15	$\frac{1}{2}(\frac{3}{2}+)$	3.86	3.85±0.03	8	7–12	5.3–5.0
		2.49		<7		
6.70		4.41		<3	8–11	5.0–4.8
		3.04	3.02±0.03	10		
6.92±0.04[g]		4.63		<2	12–14	4.7–4.6
			3.26±0.04	15		
		0.51		e		
7.14	$(\frac{3}{2})$	4.85	4.82±0.03	17	≲47	≳4.1[f]
		3.48	3.47±0.03	≲39[f]		
		0.73		<3		
7.25±0.03[g]			4.95±0.05	2	22	4.3
			3.63±0.04	11		
			0.82±0.05	14		
7.90±0.02[h]	$(\frac{5}{2}+)$		5.57±0.04	20	100	[3.3]
	$T=\frac{3}{2}$		4.25±0.02	100		
		1.49		<7		
8.20±0.03[g]			5.90±0.05	2	17	3.9
			4.54±0.03	7		
			1.80±0.03	11		
8.97±0.04[i]		6.68		≈1	6–10	3.9–3.6
	$(T=\frac{3}{2})$		5.31±0.03	6		
		2.56		<7		

[a] First number is for the transition to the 0+ ground state of Mg^{24}. Second number is for the 2+ first excited state. Third number is for the 4+ second excited state.
[b] Relative to the most intense proton peak at $E_{c.m.}=4.25$ MeV.
[c] Relative to the most intense beta transition to the 7.90-MeV level.
[d] Normalized to $\log ft=3.3$ for the transition to the 7.90-MeV level.
[e] Below the proton-energy region observable in this experiment. However, it is expected on the basis of transmission coefficients that these values would be <2.
[f] The ground-state transition from the 5.81-MeV level is included with the first excited-state transition from the 7.14-MeV level.
[g] Proposed on the basis of this work.
[h] Reported in Ref. 5 as 7.91 MeV.
[i] Tentatively proposed in Ref. 5 as 9.03 MeV.

proton decay energy ($E_{c.m.}$) to the ground and excited states of Mg^{24} for all the included known levels. These may be compared with the experimental proton decay energies listed in column 4 according to the transitions to which we have assigned them. The agreement between predicted and experimental proton decay energies is within the experimental error in all cases. The error listed with each proposed level in column 1 is the standard deviation of the level energy calculated from the observed proton peaks. Column 5 gives the relative intensity of each proton peak with the assumption that the most intense peak equals 100. Where peaks were expected but not seen, upper limits are given for the relative intensity. In column 6 these intensities have been combined and renormalized to give the total beta-decay branch to each level relative to 100 for the analog state branch. As described below, we can use a theoretically calculated $\log ft$ of 3.3 for this branch. The partial half-life for this beta transition is then 3.5 sec using an estimated Q_β of 12.3 MeV as described below. We then use the relative intensities to obtain partial half-lives for all the other transitions. The partial half-life and $E_{\beta\max}$ for each level then give us the $\log ft$ listed in column 7 for each beta transition. The sum of the inverse partial half-lives to the proton-emitting states multiplied by the Si^{25} half-life yields a total delayed-proton branch of one-fifth of all the beta decays. The analog-state decay accounts for one-third of the delayed-proton branch.

The decay scheme consistent with our observations is presented in Fig. 3. The proton-emitting levels plus other levels which could be populated by allowed beta decay are shown. The $\log ft$ for the ground state and 0.95, 1.61, and 1.81-MeV states are assumed to be equal to those found in the mirror decay of Na^{25} to Mg^{25}. These values are 5.2, 5.2, 5.6, and >5.9, respectively.[7] Since no other information is known about the $\log ft$'s for the 2.69- and 2.74-MeV states, we have used our observed half-life and all the other $\log ft$ values to calculate that approximately 36% of the transitions lead

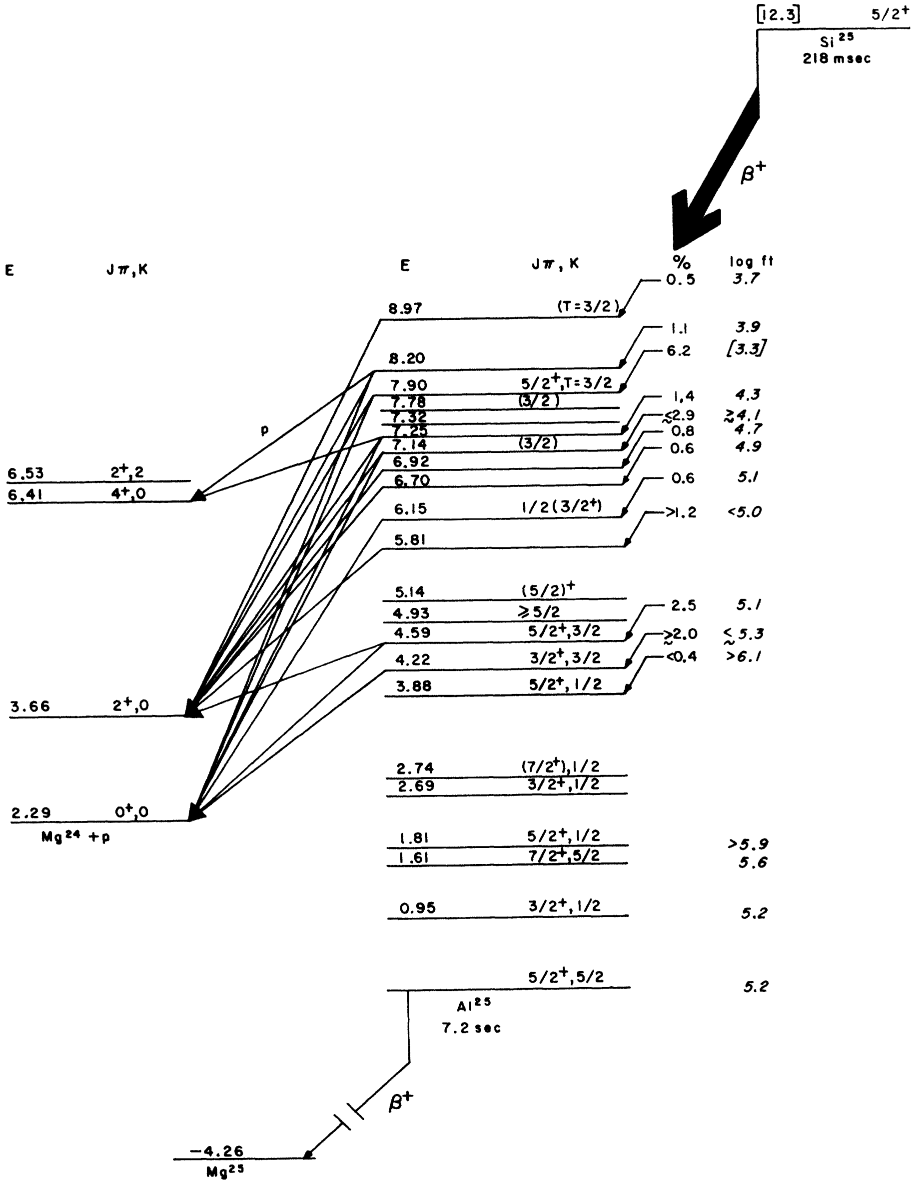

FIG. 3. Energy levels of Al^{25} from Ref. 7. States which could not be populated by allowed beta decay are not shown. Energies are relative to the Al^{25} ground state. The previously known $(J\pi,K)$ assignments are shown. Transitions corresponding to the delayed-proton peaks in Fig. 1 and Fig. 2 are indicated. Based on these proton peak assignments the beta transitions are indicated. The percent abundance and log*ft* values are given by normalizing to a calculated log*ft* of 3.3 for the 7.90-MeV level as described in the text. The log*ft* values to the bound levels are from the mirror decay of Na^{25}.

to these two states. This is consistent with the two unknown log*ft* values each having the reasonable value of 4.7.

Our assumptions for the superallowed log*ft* and for Q_β are as follows. That the log*ft* value for the superallowed transition may be calculated within close limits was pointed out by Hardy and Margolis.[4] This is because the Fermi matrix element is large ($\langle 1\rangle^2=3$) and is not model-dependent. The Gamow-Teller matrix element (σ) for a single-particle transition between states of $T=\frac{3}{2}$ is multiplied by the factor $1/\sqrt{3}$ and is therefore small. They calculated the Gamow-Teller matrix element using the Nilsson formalism and arrived at a value of $\sigma^2=0.24$ which gives a log*ft* value of 3.27. They assumed the wave function describing Si^{25} as having $J\pi K=\frac{5}{2}+\frac{5}{2}$. It has been pointed out (Litherland *et al.*[12]) that the β decay of the mirror, Na^{25}, indicates $J\pi K=\frac{5}{2}+\frac{3}{2}$. For the ground state to be so inverted the wave function would best be described by a mixture of at least two K bands. Indeed, the first excited state of Na^{25} is only 90 keV above the ground state.[7] For a pure $K=\frac{3}{2}$ description σ^2 would be 0.05 resulting in a log*ft* of 3.31, which is only slightly different from that for $K=\frac{5}{2}$.[13] In the limit of a $d_{5/2}$ single-particle transition, $\sigma^2=7/15$ for a log*ft* of 3.23. This superallowed log*ft* has

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[12] A. E. Litherland, H. McManus, E. B. Paul, D. A. Bromley, and H. E. Gove, Can. J. Phys. **36**, 378 (1958).

[13] If transitions to both states of the doublet contribute to the observed 7.90-MeV level, the transition rate would be increased only by the additional Gamow-Teller matrix element involved.

been measured by Hardy, Verrall, and Bell[14] by comparing the delayed proton yield with that of known $\log ft$ values in the Ne^{17} decay. They assumed that the $(p,3n)$ cross sections for producing Si^{25} and Ne^{17} at 100 MeV were in the ratio of the total reaction cross sections. The value they obtained was 3.0±0.3. Thus, since the calculated $\log ft$ appears so model-independent and in agreement with the measured value, it seems reasonable to adopt the value 3.3 for this superallowed transition.

Q_β was estimated using a method proposed by Wilkinson[2,15] for the masses of isobaric quarters: $M_{-3/2}-M_{3/2}=3(M_{-1/2}-M_{1/2})$ where M_x represents the ground state mass of an isotope with $T_z=x$. The value obtained was $Q_\beta=12.3$ MeV. Very recently it has come to our attention[16] that the position of the lowest $T=\frac{3}{2}$ state in Mg^{25} has been measured. This allows use of the above formula with masses of $T=\frac{3}{2}$ states only, and a better estimate of Q_β is 12.6±0.1 MeV. This value of Q gives $\log ft$ values which are less than 0.1 of a $\log ft$ unit different from those calculated using $Q_\beta=12.3$. Table II and Fig. 3 have not been revised, since the error on the relative beta intensities may be as large as 0.3 of a $\log ft$ unit in some cases.

We have ignored the problem of competition between gamma emission and proton emission for states just above the proton binding energy. Gamma rays have been seen from the states at 3.88, 4.22, and 4.59 MeV.[7] By comparing the gamma widths to the total widths of these states it is found that their gamma branches in percent are 0.05, <0.3, and <0.01. Since it is expected that gamma competition from the higher energy levels would be even less in general, we feel justified in neglecting gamma competition in calculating the $\log ft$ values. There is no alpha-particle competition because the separation energy of an alpha particle from Al^{25} is 9.2 MeV.

Two of the proton peaks have been assigned as transitions to the 4+ second-excited state of Mg^{24} from the new levels at 7.25 and 8.20 MeV. In each case these transitions are more intense than the higher energy transitions to the ground and first excited states, suggesting $l=0$ proton emission to the second excited state. This is supported by the calculated transmission coefficients. If the 7.25- and 8.20-MeV levels are populated by allowed beta decay of a $\frac{5}{2}+$ parent and emit s-wave protons to a 4+ daughter state then they would have spin-parity of $\frac{7}{2}+$.

The assignment of certain proton peaks to particular transitions is ambiguous in a few cases. One should bear in mind the following comments when examining the decay scheme in Fig. 3.

8.97-MeV level. The proton peak at 5.31 MeV in Fig. 1 has been assigned to a first excited-state transition from a new level at 8.97 MeV. The corresponding ground-state transition in the one spectrum taken with sufficient detector bias was somewhat obscured by a pulser peak. However, Hardy and Bell did see an indication of this peak.[5] The transition to the second-excited state of Mg^{24} would be at 2.56 MeV. However, in this energy region we also expect a peak at 2.64 MeV for the ground-state decay of the 4.93-MeV level and a peak at 2.49 MeV for the first excited-state decay of the level at 6.15 MeV. Some of these transitions may give rise to the broad hump in Fig. 1 in this energy region. It is conceivable that the 5.31-MeV proton peak is due to the ground-state decay of a new level at 7.60 MeV. However, we would then be able to set an upper limit of 3% for a first-excited-state transition from such a level.

8.20-MeV level. The proton decay energy between the 8.20-MeV level and the second-excited state of Mg^{24} is 1.80 MeV which agrees exactly with the experimental peak at 1.80±0.03 MeV. However, the peak might also be due to a 1.76-MeV transition from a known level at 4.05 MeV to the ground state of Mg^{24}. Other work has given a tentative assignment of $\frac{9}{2}+$ to this level. Assuming that the proton peak is from this level, the $\log ft$ must be less than 5.8 which would be possible only if the spin assignment for the 4.05-MeV level is wrong.

7.25-MeV level. The proposed level at 7.25±0.03 MeV accounts for observed proton peaks at 4.95, 3.63, and 0.82 MeV. A level reported by Batchelor *et al.*[17] at 7.32±0.03 MeV is just outside the error on our determination of this level energy. The 0.82-MeV peak occurs at the same position as the ground-state decay of a known level at 3.08 MeV. However, since this is a $\frac{3}{2}-$ state, beta decay to populate this state is forbidden. If the 0.82-MeV peak came from a first-excited state transition, we would need a new level at 4.48 MeV. The ground-state decay of such a level would appear at 2.19 MeV. This would overlap the excited state transition of 2.15 MeV from the 5.81-MeV level and might be missed. However, a level at 4.48 MeV would probably have been seen in previous studies if it exists, so we prefer to assign the 0.82-MeV peak to the proposed level at 7.25 MeV.

6.92-MeV level. The new level at 6.92±0.04 MeV is based on only one observed proton peak. If this were a ground-state transition, it would require a new level at 5.55 MeV. The excited-state transition, which is likely to be at least as intense, would occur at an $E_{\mathrm{c.m.}}$ of 1.89 MeV which is in the valley between two other peaks. Thus we have assigned the observed proton peak to the first excited-state transition of a new level at 6.92 MeV, although the choice is somewhat ambiguous.

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[17] R. Batchelor, A. J. Ferguson, H. E. Gove, and A. E. Litherland, Nucl. Phys. 16, 38 (1960).

5.81-MeV level. The ground-state decay of the 5.81-MeV level was not observed. This transition of 3.52-MeV $E_{c.m.}$ could well be hidden under the 3.48-MeV transition from the 7.14-MeV level to the first-excited state of Mg^{24}. The energy of the experimental peak was 3.47 ± 0.03 MeV so we have assumed that most of the intensity is due to the latter transition.

Unobserved levels. Transitions from the level at 7.78 MeV would probably not have been seen if they occurred because the level is known to be 340 keV wide[7] and the peaks would have been too broad. Transitions from the level at 7.32 MeV could have been seen if the $\log ft$ feeding this level was less than six. Transitions from the levels at 4.93 and 5.14 MeV were not seen. This probably indicates that these levels are not populated by allowed beta decay. Neither had definite spin-parity assignments. The level at 3.88, which had been assigned $\frac{5}{2}+$, was not seen. An upper limit for its intensity is given in Table II, and corresponds to a $\log ft > 6.1$.

It is clear that all the ambiguities in these assignments could be resolved by measuring the delayed-proton spectrum in coincidence with the gamma rays associated with the excited levels of Mg^{24}. In a preliminary experiment we measured the proton spectrum in coincidence with the 1.37-MeV gamma ray from the first-excited state of Mg^{24} and were able to show that the 4.25-MeV peak was associated with the 1.37-MeV gamma ray. However, the statistics and background were too poor to show any other features.

DISCUSSION

The deformed nucleus Al^{25} is well known because of the impressive success of the Nilsson model in categorizing the excited states up to 5 MeV. These lowest excited states are well described by five rotational bands based on excitations of a single odd proton in an axially symmetric Mg^{24} core.[7,12] At higher excitation energy, because of the increased density of states and the lack of spin-parity assignments, the simple interpretation had not been pursued. We have shown that allowed beta decay of Si^{25} populates seven $T=\frac{1}{2}$ positive parity states with spins $\frac{3}{2}$, $\frac{5}{2}$, and $\frac{7}{2}$ above 5 MeV. In the above model two of these states might fit into existing bands. Unless a $g_{9/2}-d_{5/2}$ splitting of only 7 MeV is invoked, the remaining five levels must be ascribed to more complicated configurations. However, the asymmetric-rotator calculation of Bar-Touv and Kelson[18] generates four more levels in this energy range with appropriate spin and parity for allowed beta decay. (These levels are about 2 MeV lower than the ones we see, but several of their levels calculated for the Mg^{24} core are also 2 MeV too low.) In addition the K mixing of the ground state of Na^{25}, which has been discussed, would be consistent with an asymmetric core. We would like to emphasize that we have observed a large number of rather small $\log ft$ values. It would be interesting to see if these $\log ft$ values as well as those for the decay of Na^{25} could be accounted for by the asymmetric-rotator model.

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