According to an $A^{1/3}$ law, we expect a change in the rms radius for a pair of isotopes in the Zn region of $\Delta R = 0.040$ fm. Examination of Table IV shows that we find this change for the ^{64}Zn-^{66}Zn pair and for the ^{68}Zn-^{70}Zn pair, while the rms radius actually decreases from ^{66}Zn to ^{68}Zn. This decrease is due to a large decrease of the skin thickness t which overcompensates the rise in the half-density radius c. This effect may be related to the fact that in the case of ^{68}Zn the $1f_{5/2}$ neutron subshell is closed. A similar observation was made in a recent inelastic ^{3}He scattering experiment[10] which was performed on the same Zn isotopes as studied in the present work.

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Beta Decay of Cl^{39}†

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The β^- decay of Cl^{39} to states of Ar^{39} has been studied using a Ge(Li) detector. Cl^{39} was produced in the reaction $Cl^{37}(t,p)Cl^{39}$ at $E_t = 3.0$ MeV by bombarding $BaCl_2$ targets enriched to 96.1% in Cl^{37}. The half-life was measured to be 56.2 ± 0.6 min. Ten γ-ray transitions were observed including seven γ rays not seen previously in the Cl^{39} decay. Ge(Li) versus NaI(Tl) coincidence measurements were used to determine the placement of these γ-ray transitions in the Ar^{39} level scheme. The measured γ-ray intensities determine new β-ray branches of $\leq 0.08\%$, $(2.61 \pm 0.11)\%$, $(2.29 \pm 0.12)\%$, and $(0.60 \pm 0.05)\%$ to Ar^{39} levels at 2093, 2358, 2503, and 2829 keV with logft values of ≥ 8.03, 6.14 ± 0.04, 5.96 ± 0.04, and 5.84 ± 0.06, respectively. The latter two logft values lead to spin restrictions of $\frac{1}{2}$, $\frac{3}{2}$, or $\frac{5}{2}$ for the 2305- and 2829-keV Ar^{39} levels and strongly suggest even parity for both states. Other previously observed β-ray branches have been confirmed. Accurate excitation energies with errors between 0.05 and 1.0 keV have been obtained for the Ar^{39} states involved.

I. INTRODUCTION

The β^- decay of Cl^{39} has apparently not been studied since 1956 when Penning *et al.*[1] observed the β and γ radiation with magnetic and scintillation spectrometers. The activity was produced via the reaction $Ar^{40}(\alpha, \alpha p)Cl^{39}$ by bombarding Ar gas with 37-MeV α particles. Cl^{39} was found to decay by emission of β groups to the ground, first, and second excited states of Ar^{39} with intensities of

$(7 \pm 2)\%$, $(8 \pm 4)\%$, and $(85 \pm 6)\%$, respectively. Three γ rays were observed with energies of 246 ± 3, 1266 ± 10, and 1520 ± 10 keV and relative intensities of 90 ± 10, 100, and 85 ± 5, respectively. The 246- and 1266-keV γ rays were shown to be in coincidence. An earlier study of the Cl^{39} decay was reported by Haslam *et al.*[2] using the reaction $Ar^{40}(\gamma, p)Cl^{39}$. They measured the Cl^{39} half-life as 55.5 ± 0.2 min.

Our interest in this problem was prompted, in part, by the expectation that further experimental results could considerably illuminate the properties of the low-lying even-parity configurations of Ar^{39}. In a shell-model description, for example, the main configuration for the Cl^{39} ground state is

$$[(1d_{3/2})^5{}_{J_d=3/2,\ T_d=3/2}(1f_{7/2})^2{}_{J_f=0,\ T_f=1}]_{J=3/2,\ T=5/2},$$

i.e., two $f_{7/2}$ neutrons coupled to the Cl^{37} ground state. The β decay of Cl^{39} should therefore proceed with considerable strength via allowed transitions to Ar^{39} levels with the configurations

$$[(1d_{3/2})^5{}_{J_d=3/2,\ T_d}(1f_{7/2})^2{}_{J_f=0,\ T_f=1}]_{J=3/2,\ T=3/2},$$

with $T_d = \frac{1}{2}$ or $\frac{3}{2}$. Energy considerations[3] show that the $J^\pi = \frac{3}{2}^+$ state with the $(1d_{3/2})^5$ core coupled to $T_d = \frac{3}{2}$ is expected to lie about 800 keV above the one with the $(1d_{3/2})^5$ core coupled to $T_d = \frac{1}{2}$. The latter $\frac{3}{2}^+$ state has been found experimentally at an excitation energy of 1517 keV, and the β transition to this state is allowed, with $\log ft = 5.7$. On this basis we expect also an allowed β transition to a $J^\pi = \frac{3}{2}^+$ level at about 2.3-MeV excitation energy in Ar^{39}.

The present investigation was therefore undertaken to check the proposed[1] decay scheme and to measure the γ-ray energies with the precision afforded by Ge(Li) detectors. It became apparent that there were additional features in the decay scheme not observed previously. These new results are reported here.

II. EXPERIMENTAL METHODS AND RESULTS

Cl^{39} activity was produced by bombarding $BaCl_2$ targets with 3.0-MeV tritons from the Brookhaven National Laboratory 3.5-MV Van de Graaff accelerator. The targets consisted of $BaCl_2$, enriched to 96.1% in Cl^{37}, of about 0.5 mg/cm^2 evaporated onto 0.026-mm-thick Ta disks. An air-water spray was used to cool the back side of the target during bombardments with a 12-μA beam of tritons, which was defocused so that the intensity was spread over an area of ~ 0.3 cm^2. Under these conditions, no significant deterioration was observed.

Following bombardments of about 2 h, the targets were carried to a low-background room where a 30-cm^3 Ge(Li) detector was situated. The detector was surrounded by a lead shield of ~ 3-cm thickness, and the front face was shielded with 12.7 mm of Lucite in order to cut down the β-ray flux. Pulses from the Ge(Li) detector, after amplification utilizing standard pole-zero and dc-restoration techniques, were analyzed with an 8192-channel analog-to-digital converter (ADC) whose output was stored in one of the two sections of a TMC 16384-channel memory unit. At selected intervals, the data were read from the memory by a magnetic tape unit.

Figure 1 shows the γ-ray spectrum recorded over a 5-h counting interval, after a waiting period of 40 min had allowed the short-lived contaminants (e.g., Al^{29}) to decay. The counting rate in the Ge(Li) detector was kept roughly constant for this measurement by changing the source to detector distance from 35 to 9 cm. The spectrum of Fig. 1 shows, in addition to those γ rays connected with the $Cl^{39}(\beta^-)Ar^{39}$ decay, six contaminant γ rays. The 1642- and 2168-keV lines are due to the reaction $Cl^{37}(t, d)Cl^{38}(\beta^-)Ar^{38}$ and decay with a half-life of 37 min.[4] The 1369- and 2754-keV γ rays originate from the $T_{1/2} = 15$-h β decay of Na^{24} formed by the (t, d) reaction on Na^{23} impurities in the target, while the 1461- and 2615-keV γ rays are due to the background radiations of K^{40} and Tl^{208}. The Ge(Li) detector resolution was about 2.3 keV for the 1332-keV line of Co^{60}.

In order to obtain more firm information on the weak peaks at 1312 and 2093 keV, the front face of the Ge(Li) detector was shielded with 12.7-mm lead to reduce relatively the high counting rate below 600 keV. This was done to obtain the maximum possible over-all counting rate consistent with good detector resolution. Portions of the resulting spectrum are shown in Fig. 2 and demonstrate clearly the existence of the 1312- and 2093-keV peaks. Since the data pertaining to Figs. 1 and 2 were read from the analyzer memory at selected time intervals, the relative time dependence of the several peaks could be investigated; the results are shown in Fig. 3 where areas of several peaks relative to the area of the 1267-keV peak are plotted as a function of time. The constancy of the measured ratios shows that all eight γ rays arise from the $Cl^{39}(\beta^-)Ar^{39}$ decay, as was known previously for the 250-, 1267-, and 1517-keV γ rays.

A. Determination of Relative Intensities

To obtain the relative intensities of the γ rays belonging to the Cl^{39} β decay, a weaker source

was produced and counted under the experimental conditions used for the data of Fig. 1, but with a fixed source-detector distance of 10.0 cm. This is especially important for the experimental determination of the relative intensities of the 250- and 1267-keV γ rays, as the relative detection efficiency changes slightly with distance due to the large energy difference. The detector efficiency-calibration spectra were therefore recorded in this same geometry with a source-to-detector distance of 10.0 cm. The relative photopeak-efficiency curve was determined using γ rays of known intensities from radioactive sources of Hf^{180m},[5] Ba^{133},[6] Ag^{108m},[7] Na^{22},[8] Co^{60},[9] Y^{88},[9] and Tl^{208},[7] where the γ-ray intensities were taken from the reference indicated. The self-absorption was negligible for the thin sources used. The efficiency ratio $\epsilon_{250}/\epsilon_{1267}$ was written as $\epsilon_{250}/\epsilon_{1267} = (\epsilon_{250}/\epsilon_{511})$

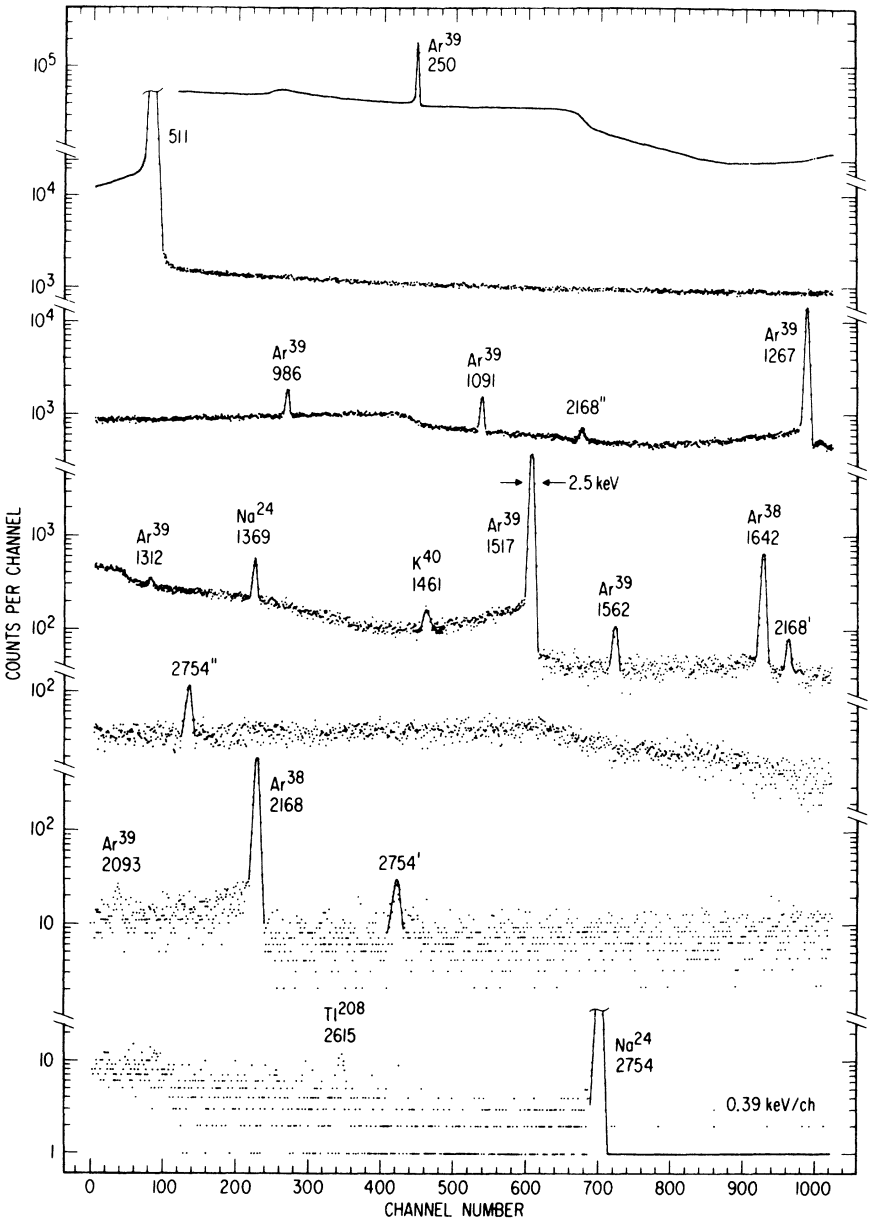

FIG. 1. Delayed γ rays observed with a 30-cm^3 Ge(Li) detector in the reaction $Cl^{37}(t,p)Cl^{39}(\beta^-)Ar^{39}$. The spectrum was recorded with an 8192-channel ADC over a 5-h counting interval after a bombardment period of 2 h and a waiting period of 40 min. A target of about 0.5-mg/cm^2 $BaCl_2$, enriched to 96.1% in Cl^{37}, was used. The peaks are labeled with the corresponding γ-ray energies in keV; primes and double primes indicate single- and double-escape peaks, respectively. The origin of the several γ rays is discussed in the text.

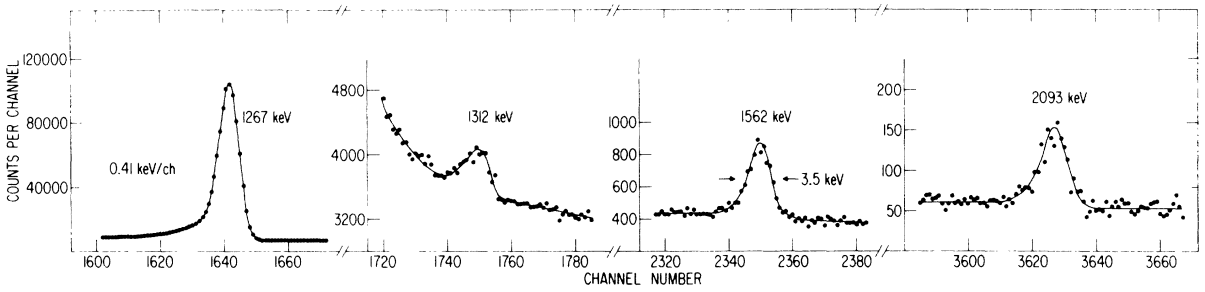

FIG. 2. Portions of the delayed γ-ray spectrum illustrating specifically the 1312- and 2093-keV transitions in Ar^{39}. These data were observed in the reaction $Cl^{37}(t,p)Cl^{39}(\beta^-)Ar^{39}$ under the same experimental conditions as in Fig. 1, but with the front face of the 30-cm^3 Ge(Li) detector shielded with 12.7 mm lead to obtain more firm information on these weak higher-energy peaks.

$\times(\epsilon_{511}/\epsilon_{1275})(\epsilon_{1275}/\epsilon_{1267})$. The first factor follows from the calibration measurements with Hf^{180m}, Ba^{133}, and Ag^{108m} sources, while the second factor is given by the measurement with the Na^{22} source. The resulting relative intensities for the several γ rays are given in Table I. The upper limits given for unobserved peaks within the given γ-ray energy intervals were taken as $4(N\times\text{FWHM})^{1/2}$, where N denotes the spectrum intensity in a particular region and values for the FWHM (full width at half maximum) were estimated from neighboring peak widths. This particular limit corresponds to two standard deviations in a result not significantly different from zero.

B. Half-Life Measurement

In order to measure the half-life of Cl^{39}, successive γ-ray spectra with durations between 0.3 and 2 h were recorded over an 11 h period after the end of bombardment. In order to minimize the necessary ADC dead-time corrections, a biased amplifier was used with the bias set to exclude pulses corresponding to energies <1180 keV. The actual correction was determined by recording the pulser peak simultaneously with the γ-ray spectra of interest. The pulser counting rate was scaled separately. The ratio of the number of scaler counts and the number of counts in the pulser peak, as observed in the measured spectrum, then gave the dead-time correction, which was in all cases smaller than 2.4%. The 1267- and 1517-keV peaks were used to determine the Cl^{39} lifetime. The analysis proceeded in the following way. The dead-time-corrected area A_i of a peak in spectrum i taken between time t_{1i} and t_{2i} can be written as

$$A_i=\int_{t_{1i}}^{t_{2i}} Ne^{-t/\tau}\,dt=Nf_i, \tag{1}$$

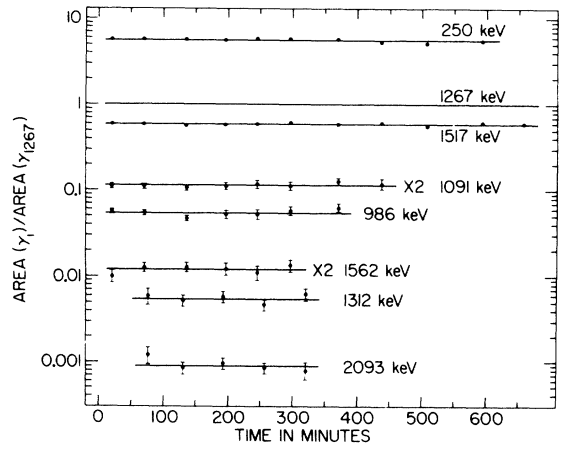

FIG. 3. Relative time dependence of the intensity of several γ rays observed in the reaction $Cl^{37}(t,p)Cl^{39}(\beta^-)Ar^{39}$. The constancy of the measured ratios shows that all eight γ rays arise from the $Cl^{39}(\beta^-)Ar^{39}$ decay, as was known previously for the 250-, 1267-, and 1517-keV γ rays.

TABLE I. Delayed γ rays from the β^- decay of Cl^{39}.

Energy (keV)	Assignment in Ar^{39} ($E_i\rightarrow E_f$ in keV)	Relative intensity
$98\le E_\gamma\le 243$		<0.3
250.26 ± 0.07	1517 → 1267	86.6 ± 3.0
$255\le E_\gamma\le 490$		<0.3
841.4 ± 1.3 [a]	2358 → 1517	0.10 ± 0.06
856.6 ± 1.3 [a]	?	0.07 ± 0.05
$530\le E_\gamma\le 975$		<0.2
985.79 ± 0.14	2503 → 1517	4.0 ± 0.2
1090.97 ± 0.11	2358 → 1267	4.7 ± 0.2
1235.4 ± 1.0 [a]	2503 → 1267	0.21 ± 0.08
1267.20 ± 0.05	1267 → 0	100
1312.1 ± 1.0	2829 → 1517	0.53 ± 0.06
1517.36 ± 0.08	1517 → 0	71.0 ± 1.5
1561.6 ± 1.0	2829 → 1267	0.58 ± 0.06
$1740\le E_\gamma\le 2080$		<0.04
2093.0 ± 1.0	2093 → 0	0.15 ± 0.02
$2250\le E_\gamma\le 2600$		<0.02
$2760\le E_\gamma\le 3260$		<0.01

[a] Observed weakly in the γ-γ coincidence measurements only (see Fig. 5).

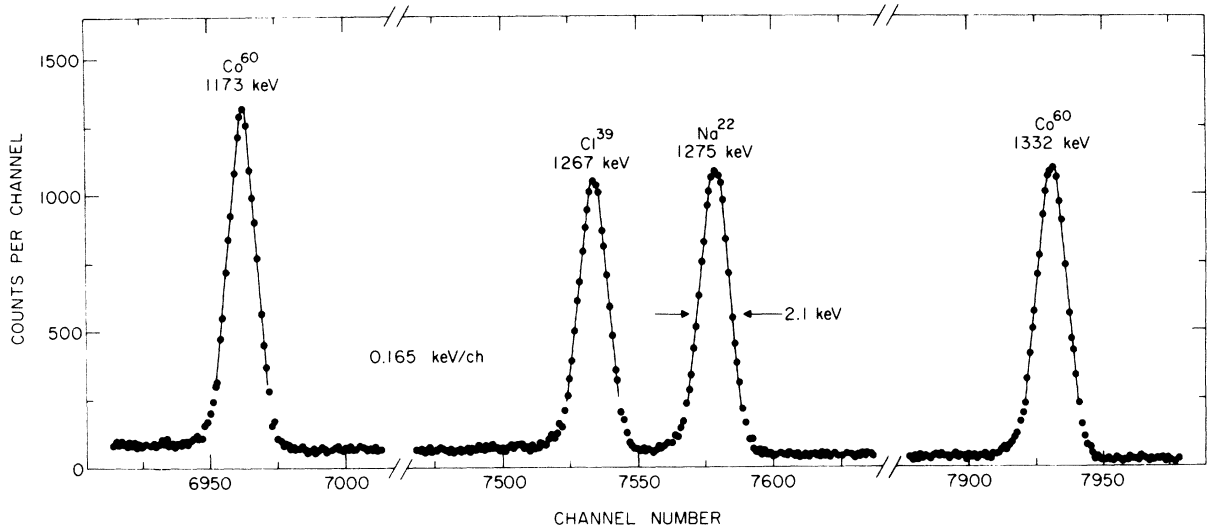

FIG. 4. Energy measurement of the 1267-keV γ ray by comparison with γ rays emitted by radioactive sources of Na^{22} and Co^{60}. The spectrum was obtained in the $Cl^{39}(\beta^-)Ar^{39}$ decay with a high-resolution 20-cm^3 Ge(Li) detector and an 8192-channel ADC.

where $f_i = e^{-t_{1i}/\tau} - e^{-t_{2i}/\tau}$ and N denotes the intensity at the end of bombardment. Minimizing the nonlinear least-squares expression

$$\sum_{i=1}^{n} \frac{(A_i - Nf_i)^2}{(\Delta A_i)^2} \tag{2}$$

(where ΔA_i denotes the error in A_i) gives the best values for N and τ. For each trial value of τ the corresponding value for N is given by $N = [\sum f_i A_i/(\Delta A_i)^2]/[\sum f_i^2/(\Delta A_i)^2]$, since Eq. (2) is linear in N. The analysis given above is more suitable than the common method of fitting a straight line to the logarithm of the data.[10] Four independent measurements of the Cl^{39} half-life lead to a mean result of $T_{1/2} = 56.2 \pm 0.6$ min. The error quoted is external; the statistical error in the separate measurements was about 0.3 min. The result obtained is in good agreement with the value 55.5 ± 0.2 min given in Ref. 2. However, the error quoted for the latter measurement may, in view of the technique used in the measurement and analysis, be somewhat underestimated.[11]

TABLE II. Excitation energies (in keV) of low-lying Ar^{39} levels.

Present	(Ref. 13) [a]	(Ref. 4)
1267.20 ± 0.05	1268 ± 5	1270 ± 5
1517.43 ± 0.06	1516 ± 5	1516 ± 8
2093.0 ± 1.0	2089 ± 5	2100 ± 10
2358.19 ± 0.12	2360 ± 5	2370 ± 10
...	...	2430 ± 20
...	2484 ± 5	2490 ± 20
2503.23 ± 0.15	2504 ± 5	...
...	...	2630 ± 10
...	2744 ± 8	...
...	(2809 ± 8) [b]	2800 ± 50
2829.2 ± 0.7	(2832 ± 10) [b]	...
...	(2890 ± 10) [b]	...
...	2941 ± 8	...

[a] Based on the present values of 1267 and 1517 keV for the separation of the ground and first excited states. Results are obtained with the reaction $Ar^{40}(He^3, \alpha)Ar^{39}$.

[b] Observed weakly.

C. γ-Ray Energy Measurements

For the γ-ray energy measurements, the mixed-source technique was used, and various spectra were recorded with dispersions between 0.088 and 0.22 keV/channel using a high-resolution 20-cm^3 Ge(Li) detector and an 8192-channel ADC. One spectrum was recorded together with Ba^{133} and Tl^{208} sources, and the energy of the 250-keV γ ray was measured relative to the 223-, 239-, and 276-keV γ rays emitted by these sources. A second spectrum taken to obtain the energy of the 1267-keV γ ray was accumulated together with sources of Na^{22} and Co^{60}, and portions of this spectrum are shown in Fig. 4. A third spectrum was taken with sources of Na^{22}, K^{40}, Co^{60}, Y^{88}, Bi^{207}, and Tl^{208} placed so that the intensities of the γ rays from these sources were comparable to the intensities of the Cl^{39} γ rays. The energies of the γ rays emitted by Na^{22}, K^{40}, Co^{60}, Y^{88}, Bi^{207}, and Tl^{208} were taken from the compilation of Marion[6]; the Ba^{133} energies are from Greenwood, Helmer, and Gehrke.[12]

The positions of the peaks of interest were determined as follows. First a least-squares fit of a

straight line was made to the data points outside the peak region. Subsequently, a least-squares fit was made to the peak assuming a Gaussian curve superimposed on this linear background. The Gaussian fits were restricted to channels for which the intensity was ≥20% of the peak intensity. The next step was to fit a polynomial to the positions of the radioactive peaks of known energy. The measure of the goodness-to-fit, χ^2, was about unity for polynomials with degree 3, 4, or 5 and degree 4 was chosen. The results are given in column 1 of Table I. The errors quoted include uncertainties in (1) peak positions, (2) radioactive calibration energies, and (3) degree of the polynomial. The γ-ray energies lead, after conversion into level-energy differences by adding $E_\gamma^2/2Mc^2$, to the excitation energies given in Table II, column 1. Column 2 shows, for comparison, results[13] obtained recently with the reaction $Ar^{40}(He^3, \alpha)Ar^{39}$.

D. Ge(Li)-NaI(Tl) Coincidence Measurements

In the γ-γ coincidence measurements, a 20-cm^3 Ge(Li) detector was used in combination with a 7.6×7.6-cm NaI(Tl) crystal. The Na(Tl) detector was situated in a cylindrical lead shield, 3 cm thick, with its front face shielded by 0.6 cm of lead. The Cl^{39} sources were sandwiched between two brass plates, each 3.2 mm thick. The Ge(Li) detector was not shielded. The two detectors were placed at an angle of 180° and 2 cm apart from each other, with the "source package" between them. Standard electronic modules provided a time spectrum with 9 nsec FWHM for γ rays of energies between 0.6 and 2.2 MeV. A time gate of 15 nsec was used throughout the measurements. The purpose of the experiment was to determine which γ-ray transitions connect to the first or second excited state of Ar^{39} at 1267 and 1517 keV, respectively. To this end the TMC analyzer was used in the spectrum-sort mode, in which 2048 channels from one detector can be recorded in coincidence with up to eight voltage gates set on the other 1024-channel spectrum. Five gates were set in the NaI(Tl) spectrum corresponding to energies of 0.66–0.96, 1.21–1.32, 1.35–1.44, 1.47–1.56, and 1.76–1.94 MeV. The coincidence spectra from the Ge(Li) detector cor-

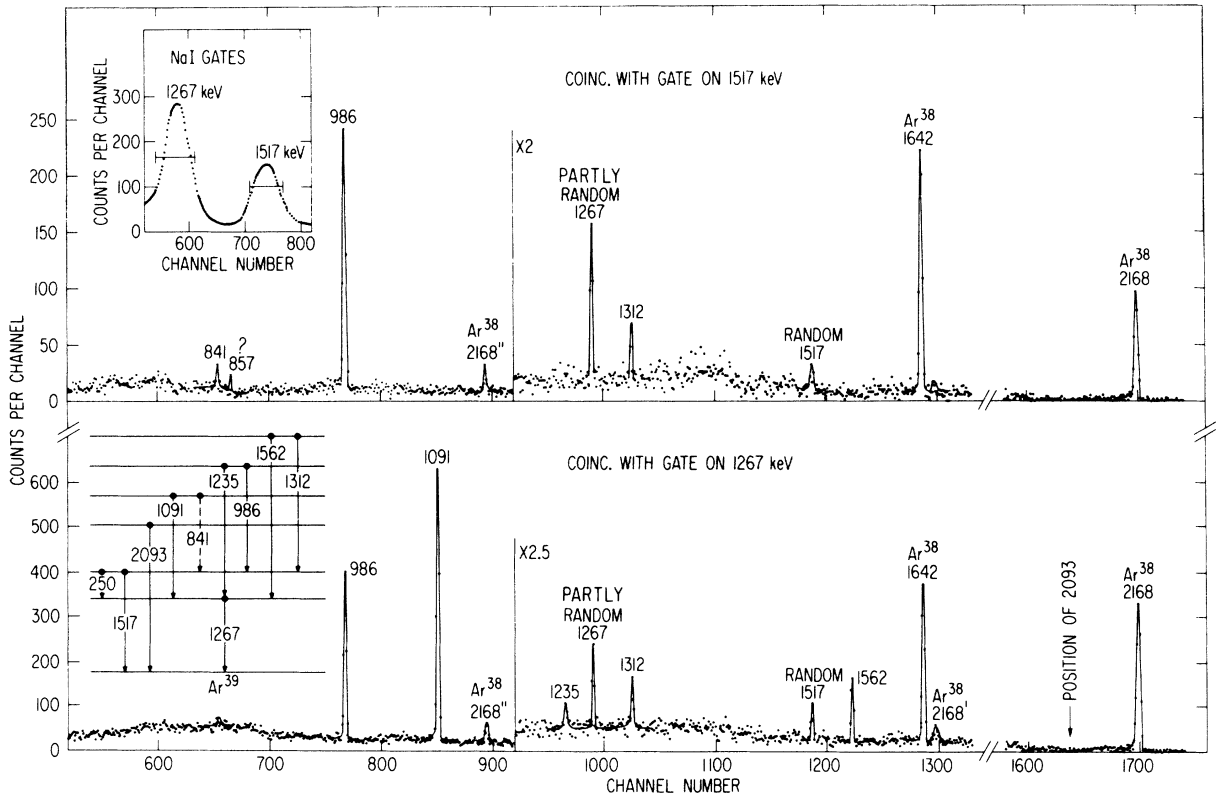

FIG. 5. γ-γ coincidence spectra observed in the $Cl^{39}(\beta^-)Ar^{39}$ decay, measured with a 20-cm^3 Ge(Li) detector in coincidence with a 7.6×7.6-cm NaI(Tl) crystal. The gates set on the 1267- and 1517-keV peaks in the NaI(Tl) spectrum are shown in the inset. The data obtained are extensively discussed in Sec. II D.

responding to the gates on the 1267- and 1517-keV γ rays are shown in Fig. 5.

With respect to the data displayed, we note that γ rays which are members of a cascade leading to the 1517-keV state will show up experimentally in the spectra coincident with both gates, since (1) the 1517-keV level branches 55% to the 1267-keV level, and (2) the gate on the 1267-keV γ ray contains also a part of the Compton edge of the 1517-keV γ ray. γ rays which connect directly with the 1267-keV state will, however, be observed only in the spectrum coincident with the gate on the 1267-keV γ ray.

The results show clearly that the 986- and 1312-keV γ rays are in coincidence with the 1517-keV γ ray. The Q value of 3438 ± 19 keV[14] for the Cl^{39}-$(\beta^-)Ar^{39}$ decay excludes the possibility that these are members of a triple cascade. Since in the singles measurement (see Fig. 1) no additional peaks below 940 keV are observed, it is concluded that the 986- and 1312-keV γ rays connect the 2503- and 2829-keV levels, respectively, with the 1517-keV level. The data show also that the 1091-, 1562-, and 1235-keV γ rays are coincident with the 1267-keV γ ray, but not with the 1517-keV γ ray. The Q value of 3438 ± 19 keV excludes the possibilities of triple cascades. Since in the singles measurement (see Fig. 1) no additional peaks below 1085 keV are observed, it is concluded that the 1091-, 1235-, and 1562-keV γ rays connect levels at 2358, 2503, and 2829 keV, respectively, with the 1267-keV level.

The well-known[15] 1642- and 2168-keV γ rays originating from the reaction $Cl^{37}(t,d)Cl^{38}(\beta^-)Ar^{38}$ show up in both spectra because both gates contain their Compton edges and the γ rays are coin-

TABLE III. γ-ray branching ratios for levels of Ar^{39} from the present results.

E_{initial} (keV)	J^{π}_{initial} [a]	E_{final} (keV)	J^{π}_{final} [a]	Branching ratio (%)
1267	$\frac{3}{2}^-$	0	$\frac{7}{2}^-$	100
1517	$\frac{3}{2}^+$	0	$\frac{7}{2}^-$	45 ± 2
		1267	$\frac{3}{2}^-$	55 ± 2
2093	$(\frac{7}{2})^-$	0	$\frac{7}{2}^-$	100
		1267	$\frac{3}{2}^-$	<80
		1517	$\frac{3}{2}^+$	<90
2358	$\frac{1}{2}^+$	0	$\frac{7}{2}^-$	<0.3
		1267	$\frac{3}{2}^-$	98 ± 1
		1517	$\frac{3}{2}^+$	2 ± 1
		2093	$(\frac{7}{2})^-$	<6
2503	$\frac{1}{2}^{(+)}, \frac{3}{2}^{(+)}, \frac{5}{2}^{(+)}$	0	$\frac{7}{2}^-$	<0.3
		1267	$\frac{3}{2}^-$	5 ± 2
		1517	$\frac{3}{2}^+$	95 ± 2
		2093	$(\frac{7}{2})^-$	<7
		2358	$\frac{1}{2}^+$	<7
2829	$\frac{1}{2}^{(+)}, \frac{3}{2}^{(+)}, \frac{5}{2}^{(+)}$	0	$\frac{7}{2}^-$	<0.8
		1267	$\frac{3}{2}^-$	52 ± 6
		1517	$\frac{3}{2}^+$	48 ± 6
		2093	$(\frac{7}{2})^-$	<16
		2358	$\frac{1}{2}^+$	<27
		2484	$(\frac{7}{2})^-$	<27
		2503	$\frac{1}{2}^{(+)}, \frac{3}{2}^{(+)}, \frac{5}{2}^{(+)}$	<27

[a] Values taken from Ref. 16. Restrictions for the Ar^{39} levels at 2503 and 2829 keV follow from the present work.

cident with each other. The appearance of the 1517-keV peak in both spectra is due to random coincidences and reflects the fact that the singles spectrum (see Fig. 1) is strongly dominated by the 1517- and 1267-keV γ rays. The intensity of the 1267-keV γ ray in both spectra is only partly due to randoms, the remainder being due to the contributions of the 1235- and 1562-keV γ rays present in the gates used.

The 2093-keV γ ray, which was observed clearly in the singles measurement (see Fig. 2), can be placed in the level scheme in two ways: namely, as a 2093 → 0- or 3360 → 1267-keV transition. In the latter case, the 2093-keV peak would show up in the spectrum coincident with the 1267-keV gate. With the (I_{2093}/I_{1563}) ratio taken from the singles measurement, one would expect at 2093 keV a peak with an area of about 20 counts, which is inconsistent with an observed average of 1.5 count per channel in this region (see Fig. 5). It is therefore concluded that the 2093-keV γ ray represents the 2093 → 0 ground-state transition.

The situation for the weak peaks at 841 and 857 keV seen in the 1517-keV gate spectrum is not clear, since the background in the 1267-keV gate spectrum in this region is much higher due to the Compton edge of the 1091-keV γ ray. The 841-keV γ ray is considered, solely on the basis of its energy, as a transition between the 2358- and 1517-keV levels, since the existence of a level at 2358 keV is established above. No attempt is made to place the weak γ ray, observed at 857 keV in the 1517-keV gate spectrum, in the Ar^{39} level scheme.

The γ-ray spectra coincident with the other three gates, which illustrate primarily the backgrounds adjacent to the 1267- and 1517-keV peaks seen by the NaI(Tl) detector, support the conclusions given above. The placement of the observed γ rays in the Ar^{39} decay scheme, as shown in the insert of Fig. 5, together with the intensity results of Table I, leads to the information about γ-ray branching ratios for Ar^{39} levels given in Table III and to the information about β-ray branches in the decay of Cl^{39} as given in Table IV.

The spin-parity assignments quoted in Tables III and IV are taken from the work of Fitz, Jahr, and Santo,[16] who studied the reactions $Ar^{38}(d, p)Ar^{39}$ and $Ar^{40}(d, t)Ar^{39}$. The spin restriction of $\frac{1}{2}$, $\frac{3}{2}$, or $\frac{5}{2}$ for the Ar^{39} levels at 2503 and 2829 keV follow from the present work. The logft values of 5.96 and 5.84 suggest strongly[17] even parity for these two states.

The ground-state β branch of $(7 \pm 2)\%$ is taken from the work of Penning *et al.*[1] Their values of $(8 \pm 4)\%$ and $(85 \pm 6)\%$ for the β branches to the Ar^{39} levels at 1267 and 1517 keV, respectively, are in good agreement with the values of $(4.3 \pm 1.6)\%$ and $(83.1 \pm 1.9)\%$ obtained in the present work. From their γ-ray spectrum, Penning *et al.*[1] set an upper limit of 0.6%, relative to the 1267-keV γ ray, on the intensity of any γ ray with an energy larger than 1.52 MeV. This upper limit agrees well with the intensities observed for the 1562- and 2093-keV γ rays in the present work (see Table I). The observed γ-ray intensity ratio of $(I_{2093}/I_{1267}) = 0.0015 \pm 0.0002$ (see Table I) does not necessarily imply a β branch to the 2093-keV level, as the γ-ray intensity could possibly be due to un-

TABLE IV. β-ray branches in the decay of Cl^{39}.

E_x (keV)	β branch (%)	E_β(max)[a] (keV)	logft[b]	logf_1t[c]	J^π[d]
0	7 ±2[e]	3438 ± 19	7.82 ± 0.12	9.32 ± 0.12	$\frac{7}{2}^-$
1267	4.3 ± 1.6	2171 ± 19	7.16 ± 0.16		$\frac{3}{2}^-$
1517	83.1 ± 1.9	1921 ± 19	5.65 ± 0.02		$\frac{3}{2}^+$
2093	≤0.08[f]	1345 ± 19	≥8.03	≥8.83	$(\frac{7}{2})^-$
2358	2.61 ± 0.11	1080 ± 19	6.14 ± 0.04		$\frac{1}{2}^+$
2503	2.29 ± 0.12	935 ± 19	5.96 ± 0.04		$\frac{1}{2}^{(+)}, \frac{3}{2}^{(+)}, \frac{5}{2}^{(+)}$
2829	0.60 ± 0.05	609 ± 19	5.84 ± 0.06		

[a] The Q value for the reaction $Cl^{39}(\beta^-)Ar^{39}$ is given in Ref. 14 as 3438 ± 19 keV.

[b] The half-life is taken as $T_{1/2} = 56.2 \pm 0.6$ min.

[c] The definition of f_1 is that given in Ref. 18, which results in f_1t values 12 times greater than the older definition; e.g., J. P. Davidson, Phys. Rev. 82, 48 (1951).

[d] Values taken from Ref. 16. Restrictions for the Ar^{39} levels at 2503 and 2829 keV follow from the present work.

[e] Value taken from Ref. 1.

[f] The observed γ-ray intensity, and therefore the inferred β-ray intensity, could be due to unobserved γ-ray feedings (see text).

detected γ-ray feedings from the higher-lying levels populated. The upper limits on these possible feedings (see Table III) are not restrictive enough to exclude this possibility. The observed intensity for the 2093-keV γ ray leads therefore only to an upper limit of 0.08% for the β branch to the 2093-keV level. The experimental results are summarized in Fig. 6.

III. DISCUSSION

The conclusions of the present experiment on the branching of the $Cl^{39}(\beta^-)Ar^{39}$ decay and on the γ-ray branching of final states in Ar^{39} are given in Tables III and IV and summarized in Fig. 6. These results are in excellent agreement with the conclusions of Penning *et al.*[1] on the major β^- decays to the Ar^{39} ground state ($J^\pi = \frac{7}{2}^-$) and to the first and second excited states at 1267 keV ($J^\pi = \frac{3}{2}^-$) and 1517 keV ($J^\pi = \frac{3}{2}^+$), respectively. Our results on the somewhat weaker transitions to the $J^\pi = \frac{1}{2}^+$ states at 2503 and 2829 keV are also quite consistent with their quoted limits.[1]

The present results restrict the possible spin assignments for the 2503- and 2829-keV levels to $J = \frac{1}{2}, \frac{3}{2}$, or $\frac{5}{2}$. The parity of each is most probably positive, since the $\log ft$ values are 5.8 and 6.0, respectively, which strongly suggests that the β transitions are allowed. This is shown by the survey of $\log ft$ values of Ref. 17 (see p. 88, Figs. 2 and 3): Forbidden transitions with $\log ft < 5.8$ have so far not been observed for nuclei with $Z < 80$.

The identification of the $\frac{3}{2}^+$ 1517-keV level as the $T_d = \frac{1}{2}$ member of the configuration

$$[(1d_{3/2})^5{}_{J_d=3/2,\ T_d}(1f_{7/2})^2{}_{J_f=0,\ T_f=1}]_{J=3/2,\ T=3/2},$$

has been discussed in Sec. I. One may speculate,

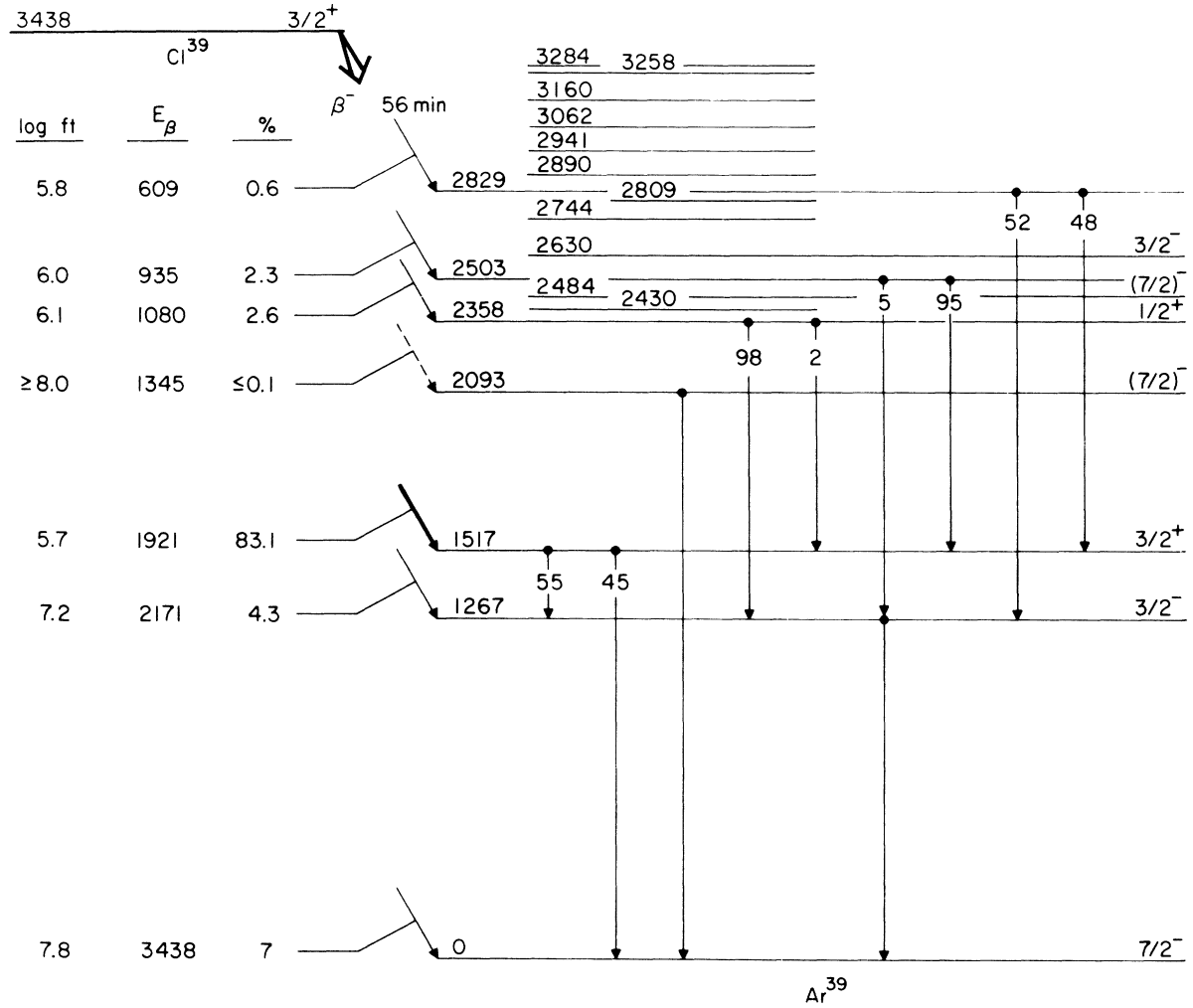

FIG. 6. Summary of the experimental information on β-ray branches, excitation energies, and branching ratios. Detailed information is found in Tables I–IV. The levels shown as not directly β fed are from Ref. 13.

on the basis of the present evidence, that the 2503-keV state is the $T_d = \frac{3}{2}$ member of this configuration. The measured excitation energy is in reasonable agreement with the prediction[3] that it should lie ~800 keV above the $\frac{3}{2}^+$ state at 1517 keV.

Kurath and Lawson[3] have investigated the $M2$ matrix elements between the $\frac{3}{2}^+$ levels with the above configurations, with $T_d = \frac{1}{2}$ or $\frac{3}{2}$, and the Ar^{39} $\frac{7}{2}^-$ ground state, which has mainly the configuration

$$[(1d_{3/2})^6{}_{J_d=0,\ T_d=1}(1f_{7/2})]_{J=7/2,\ T=3/2}\,.$$

Their calculations predict that the $M2$ transition deexciting the upper $\frac{3}{2}^+$ level should be stronger by a factor of about 3.5 than the $M2$ transition from the lower $\frac{3}{2}^+$ state at 1517 keV. Since the latter $M2$ transition has a strength[4] of about 0.16 W.u. (Weisskopf units), an $M2$ strength of about 0.6 W.u. would be expected for the 2503 → 0 transition. This would correspond to a partial mean life for $M2$ decay of 65 psec or to a total mean life for the 2503-keV level shorter than 0.2 psec, since the $\frac{3}{2}^+ \rightarrow \frac{7}{2}^-$ branch is experimentally smaller than 0.3% (see Table III). With respect to the other decay modes this result of $\tau < 0.2$ psec leads to an $M1$ strength >0.15 W.u. for the 2503 → 1517 transition and to an $E1$ strength >0.0001 W.u. for the 2503 → 1267 transition. Both are reasonable limits. In summary, a mean life of about 0.1 psec for the $\frac{3}{2}^+$ 2503-keV level would be in agreement with the theoretical expectations as well as with the experimental decay data now available. In this context it is worthwhile to note that the upper $\frac{3}{2}^+$ level (tentatively identified with the level at 2503-keV excitation energy) should be populated strongly in the reaction $Cl^{37}(He^3, p)Ar^{39}$, since the Cl^{37} ground state has mainly the configuration $(1d_{3/2})^5{}_{J_d=3/2,\ T_d=3/2}$.

The β decay to the $\frac{7}{2}^-$ Ar^{39} ground state is unique first-forbidden. This decay has been theoretically investigated[18] and found to be quite well described by an extended shell model which includes correlations induced by the repulsive $T=1$ particle-hole force. The 2093-keV level of Ar^{39} is also most probably $\frac{7}{2}^-$. If so, then the decay to it would be unique first-forbidden, and the appropriate information from the limit on the β-branching ratio is a limit on $\log f_1 t$. From Table IV we see that this limit corresponds to a quite strong unique first-forbidden decay (no $\log f_1 t$ values less than 9.0 have been reported[18]). Thus, if the 2093-keV level has $J^\pi = \frac{7}{2}^-$, it is probable that the Ar^{39} 2093 → 0 transition observed in the present work arises mainly from undetected γ-ray feeding from the 2503- and/or 2829-keV levels.

Some previous information on the γ decay of Ar^{39} states has been presented by Bass and Saleh-Bass[19] who studied the $K^{39}(n, p\gamma)Ar^{39}$ reaction with NaI(Tl) crystals for γ-ray detection. In view of the Ar^{39} level density (see Fig. 6), as compared to typical NaI(Tl) resolutions, some caution should be exercised in a comparison of branching ratios for the states above 2.2 MeV. Their conclusions for the three excited states reported below 2.2-MeV excitation energy, however, are in good agreement with the present results. In particular, they observe a level at 2.10 ± 0.01 MeV which decays predominantly to the ground state $(81.5 \pm 7.5)\%$ with weak branches of $(10 \pm 2.5)\%$ and $(8.5 \pm 3)\%$ to the 1267- and 1517-keV states, respectively. The placement, within the Ar^{39} level scheme, of the 2093-keV transition seen in the Cl^{39} β decay is in agreement with this result.

For the higher-lying states, the experimental γ-γ *coincidence* results of Bass and Saleh-Bass are not inconsistent with our conclusions, shown in Fig. 6. However, they report strong ground-state transitions from levels in this region of excitation energy, which suggests that the (n, p) reaction populates levels other than those seen in the β decay. The assignment of these ground-state branches to a particular state is, in view of the NaI(Tl) resolution, at best, tenuous. The further unravelling of the Ar^{39} level scheme must therefore clearly await other high-resolution studies of the γ-decay radiations.

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Beta Decay of the ^{26}Al Ground State*

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The decay scheme of the ground state of ^{26}Al has been reexamined by measurement of its γ-ray spectrum with Ge(Li) detectors. The γ-ray spectrum shows very strong positron annihilation radiation, a strong peak at 1808.65 ± 0.07 keV, a weak peak at 1129.67 ± 0.10 keV, and a very weak peak at 2938 keV. These γ-ray energies correspond to transitions from the first and second excited states of ^{26}Mg, which have been determined more accurately in this experiment. The ^{26}Al branching ratios, calculated from the γ-ray relative intensities, are (82.1 ± 2.5)% positron emission to the 1809-keV level, (15.2 ± 2.5)% electron capture to that same level, and (2.7 ± 0.2)% electron capture to the 2938-keV level of ^{26}Mg. The 2938-keV state decays (10.2 ± 2.0)% directly to the ground state and (89.8 ± 2.0)% by cascade. These branching ratios combine with previous results to give a half-life of (7.16 ± 0.32) × 10^5 yr for the ground state of ^{26}Al.

I. INTRODUCTION

The decay of the ground state of ^{26}Al to ^{26}Mg has not been investigated since 1958–59. At that time it was established that the 5^+ ^{26}Al ground state decays to two 2^+ states of ^{26}Mg at 1.81 and 2.97 MeV with branching ratios of (96.0 ± 0.3) and (4.0 ± 0.3)%, respectively.[1] It was determined that the major branch was composed of (84.6 ± 1.8)% positron emission and (11.4 ± 1.9)% electron capture (EC).[1] The positron spectrum has a unique second-forbidden shape,[2,3] and an end point of 1160 ± 8 keV. Because the energy release is barely above $2m_0c^2$, the decay to the 2938-keV level proceeds by EC with a negligible positron-emission component. The partial half-life for positron emission to the 1.81-MeV level was measured with a 4π Geiger-Müller counter and mass-spectrometric analysis to be (8.73 ± 0.30) × 10^5 yr.[4] The half-life of the ^{26}Al ground state was thus determined to be (7.38 ± 0.29) × 10^5 yr.[1,4]

There are several reasons why a reinvestigation of the decay of ^{26}Al was believed worthwhile. First, earlier work[1,5] on the branching ratios was carried out using NaI(Tl) crystals to detect γ rays, and it was felt that more reliable measurements could be made with Ge(Li) detectors. Second, recent calculations[6] of the expected ratio of EC to positron emission (β^+) in the decay to the 1.81-MeV level revealed that the branching ratios of Rightmire, Simanton, and Kohman[1] differ from the expected result by 2.5 standard deviations. Since the EC-to-β^+ ratio is essentially determined by atomic and not nuclear configurations, it is something that should be readily and reliably calculable. Thus, if this discrepancy is real, it is quite serious indeed. For these reasons, then, an investigation of the relative decay modes of ^{26}Al was undertaken.

II. EXPERIMENTAL PROCEDURE AND RESULTS

The source[7] of ^{26}Al was a solution of $Al(NO_3)_3$ with a nominal activity of 10^5 disintegrations per min (0.045 μCi) which was evaporated to dryness as