one of the two neutrons in the $\frac{1}{2}[211]$ orbital to pair off with the extra core $\frac{3}{2}[202]$ neutron) with the third excited state as a rotational band member gave the correct energy separation of these states with reasonable values of the collective model parameters.

A detailed calculation of the angular distribution to these states has not been attempted in the present work, however, some qualitative information can be gained from the amplitudes $A_{NLSJ}[I_fK_f;\Omega_1\Omega_2;I_iK_i]$. The experimental data for these two states are shown in Fig. 7. Unfortunately, a configuration based on a neutron-hole excitation cannot contribute to the reaction amplitude of the present model, and we can therefore not comment on the possibility of this mode of excitation. However, the amplitudes for a first excited state configuration based upon both captured particles entering the $\frac{3}{2}[202]$ orbital coupled to $\Omega=0$ are consistent with the observed forward peaking of the first excited state and the lack of forward peaking in the third excited state angular distributions. Finally, the negative results of Bishop for an excited state based upon the lifting of the extra core neutron are supported here by the fact that the amplitudes for a third excited state as a rotational band member of this configuration predict a forward-peaked angular distribution, contrary to the observed results.

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Positron Decays of ^{38}Ca and ^{38}K

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The positron decay of ^{38}Ca has been investigated using the ^{36}Ar(^{3}He,n) reaction with an enriched ^{36}Ar gas target. A delayed 1568-keV γ ray with a half-life of 0.47 ± 0.02 sec is attributed to a positron branch to the 1695-keV level of ^{38}K. Upper limits of 3% or better were found for transitions to other low-lying levels. Using the measured half-life and the decay energies, the branching ratio to the 1695-keV level is calculated from β-decay systematics to be $(21\pm4)\%$. The logft for this transition (3.41 ± 0.09) establishes $J^\pi=1^+$ for the 1695-keV level. An additional result was the observation of an allowed transition from ^{38}K to the 3936-keV level of ^{38}Ar.

I. INTRODUCTION

The isotope ^{38}Ca has a mass 6736 ± 27 keV greater than ^{38}K, and must therefore decay by superallowed β^+ emission to its isobaric analog level ($J^\pi=0^+$, $T=1$) at an excitation of 127 keV in ^{38}K.[1] The only reported evidence relating to this decay has been that of Cline and Chagnon,[2] who irradiated Ca and CaH$_2$ targets with 85-MeV bremsstrahlung and attributed a delayed γ ray, with energy 3.5 ± 0.1 MeV and half-life 0.66 ± 0.05 sec, to the reaction ^{40}Ca$(\gamma,2n)^{38}$Ca$(\beta^+\gamma)^{38}$K. The assignment was based in part on the good agreement between the observed half-life and an earlier semiempirical estimate of 0.7 sec.[3] Using current, more accurate values for the total decay energy, $W_0=6098\pm28$ keV, and for the comparative half-life for such 0^+-to-0^+ transitions, $ft=3100\pm30$ sec,[4] one finds the corresponding partial half-life for ^{38}Ca to be 0.593 ± 0.015 sec, also reasonably close to the observed value.

In view, however, of the systematic presence[5] of strong Gamow-Teller transitions in the $A=4N+2$ series of nuclei up to ^{30}P, the present work was undertaken to search for γ rays following β^+ transitions from ^{38}Ca to $J^\pi=1^+$ states of ^{38}K. One such was indeed found leading with a calculated relative intensity of $21\pm4\%$, to the known 1.7-MeV level of ^{38}K, and its half-life was measured to be 0.47 ± 0.02 sec, in disagreement with the observation of Cline and Chagnon.

In the course of this work, a previously unreported transition from 7.68-min ^{38}K to the fourth excited state of ^{38}Ar was also observed.

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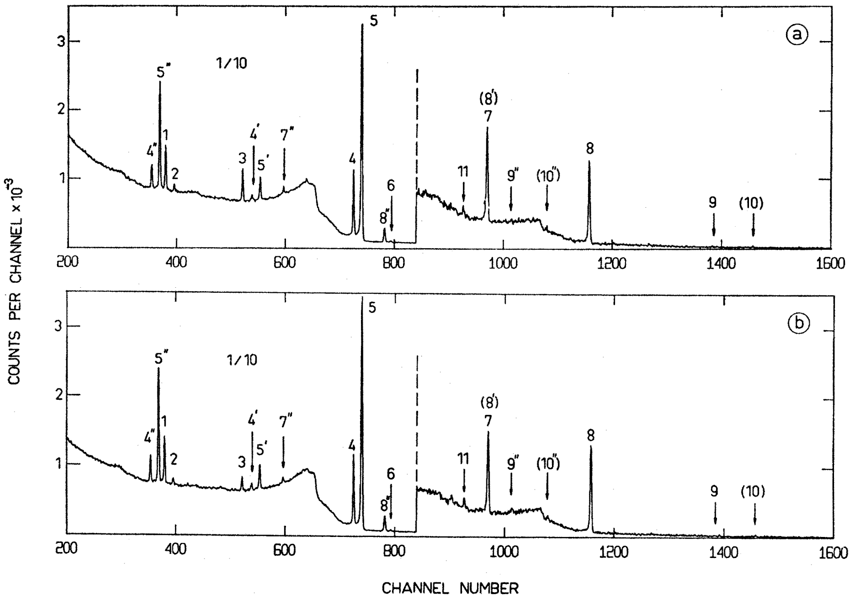

FIG. 1. Spectra of delayed γ rays in 22-cm^3 Ge(Li) after 11-MeV ^{3}He bombardment of ^{36}Ar. Figure 1(a) is the spectrum observed in the interval from 100 to 692 msec after the end of a beam burst ($\approx\frac{1}{2}$ sec), and Fig. 1(b) is that observed in the next 654 msec. However, to improve the visibility of the short-lived activities, the two spectra have been normalized (i.e., corrected for dead-time and counting-interval differences) so that long-lived activities appear with equal intensities. The three peaks arising from a given γ ray through pair production are distinguished by primes, e.g., 8, 8', and 8'', for E_γ, $E_\gamma-mc^2$, $E_\gamma-2\,mc^2$, respectively. The short lifetime of the 1568-keV γ ray (line 3), due to ^{38}Ca, is readily seen. Line 7'', the pair peak of the decay of ^{37}Ar (2.795), also has a small contribution from the 1775-keV γ ray of ^{28}Al (β^-), from activation of the aluminum in the target cell or Ge(Li) housing. Line 11 is attributed to the sum of the 2168-keV γ ray from ^{38}K decay with one annihilation quantum. See Table II for further assignments.

II. EXPERIMENTAL METHOD

The ^{38}Ca was produced in the reaction ^{36}Ar(^{3}He,n), using an 11-MeV ^{3}He^{++} beam from the 5.5-MV Van de Graaff at Strasbourg, and a gas target enriched to >99.9% ^{36}Ar. The gas at a pressure of 0.75 atm was retained in a 0.5-cm^3 gold-lined aluminum chamber by an entrance foil of 8-mg/cm^2 platinum. The energy loss of the beam was about 1.1 MeV in the foil and 0.4 MeV in the gas. The beam was collimated to a 2-mm diam with tantalum apertures.

Gamma rays were observed at 90° with a 22-cm^3 Ge(Li) detector having a resolution about 3.8 keV, at the count rates used, for 1.33-MeV γ rays. The energy scale was calibrated with well-known radioactive sources, ThC'' and ^{60}Co.

The study of delayed γ rays was done using a stable electronic sequence timer to program an activation-

TABLE I. Radioactive isotopes produced by 11-MeV ^{3}He bombardment of ^{36}Ar.[a]

Isotopes	Reactions	Q(MeV)	Activity	$T_{1/2}$	E_γ(MeV)
^{38}K	^{36}Ar(^{3}He,p)	+6.196	β^+	7.68 min	2.168
^{38}K^m	^{36}Ar(^{3}He,p)	+6.069	β^+	0.95 sec	...
^{35}Ar	^{36}Ar(^{3}He,α)	+5.326	β^+	1.80 sec	1.220 1.762
^{37}Ar	^{36}Ar(^{3}He,2p)	+1.07	EC	34.8 days	...
^{34}Cl	^{36}Ar(^{3}He,$p\alpha$)	−0.57	β^+	1.57 sec	...
^{34}Cl^m	^{36}Ar(^{3}He,$p\alpha$)	−0.71	β^+,γ	32.2 min	0.146 1.177 2.127 3.304 4.119
^{37}K	^{36}Ar(^{3}He,d)	−3.637	β^+	1.23 sec	2.80
^{34}Ar	^{36}Ar(^{3}He,αn)	−7.40	β^+	0.9 sec	0.67
^{31}S	^{36}Ar(^{3}He,2α)	−1.16	β^+	2.61 sec	1.266
^{36}Cl	^{36}Ar(^{3}He,3p)	−7.65	β^+,EC,β^-	3.07×10^5 yr	...
^{38}Ca	^{36}Ar(^{3}He,n)	−1.322	β^+	0.66 sec	3.5

[a] The numbers in this table were taken from Ref. 1.

TABLE II. Delayed γ rays observed after 11-MeV ^{3}He bombardment of ^{36}Ar.

Line No.[a]	E_γ keV	I_γ %	Transition	Radioactivity	E_γ[b] keV
1	1175.8 ± 0.5	27 ± 3	^{34}S $(3.304\rightarrow2.127)$	^{34}Cl^m (β^+)	1176.1 ± 1.1
4	2127.5 ± 0.5	100	^{34}S $(2.127\rightarrow0)$		2126.7 ± 0.8
8	3303.5 ± 1.0	26 ± 2	^{34}S $(3.304\rightarrow0)$		3303.6 ± 0.9
(10)	(4116 ± 4)	(0.4 ± 0.2)	^{34}S $(4.119\rightarrow0)$		4118.6 ± 1.1
2	1218.5 ± 0.5	100	^{35}Cl $(1.220\rightarrow0)$	^{35}Ar (β^+)	1220 ± 3
	1762	<35	^{35}Cl $(1.762\rightarrow0)$		
3	1567.7 ± 0.5	100	^{38}K $(1.695\rightarrow0.127)$	^{38}Ca (β^+)	
7	2794.4 ± 0.8	100	^{37}Ar $(2.795\rightarrow0)$	^{37}K (β^+)	2802 ± 8
5	2167.3 ± 0.5	100	^{38}Ar $(2.168\rightarrow0)$	^{38}K (β^+)	2167.61 ± 0.14
9	(3936 ± 1)	(0.33 ± 0.12)	^{38}Ar $(3.936\rightarrow0)$		3936.1 ± 0.5
6[c]	2313 ± 1	100	^{14}N $(2.312\rightarrow0)$	^{14}O (β^+)	2312.68 ± 0.10

[a] The numbering is that used for the peaks in Fig. 1.
[b] Values are from Ref. 1 except for that for ^{14}N, which is from C. Chasman, K. W. Jones, R. A. Ristinen, and D. E. Alburger, Phys. Rev. **159**, 830 (1967).
[c] Transition due to radioactivity of ^{14}O, produced by the reaction ^{12}C(^{3}He,n).

measurement cycle, consisting of bombardment for a time t_0, followed—starting about 75 msec after magnetic deflection of the beam onto a remote tantalum plate—by the storage of the spectra in two successive intervals, t_1 and t_2, in separate halves of a 4096-channel analyzer. The set of times (t_0, t_1, t_2) was adjustable to facilitate the determination of half-lives from the ratio of counts, N_1 and N_2, observed in a particular γ-ray peak during t_1 and t_2, respectively. For ^{38}Ca, two different cycles were used, (440, 838, 767) msec and (440, 592, 654) msec, as measured before and after the runs with a crystal oscillator gated by the various signals used to control the cycle. Observed timing drifts were negligible, but correction of the ratio N_1/N_2 was necessary because of decreasing dead time as activities decayed during the counting periods. This correction, typically about 4%, was found experimentally from the stored counts from a pulser which was always connected to the preamplifier input. An estimated uncertainty of $<1\%$ in N_1/N_2 remained, due to error in the dead-time correction caused by beam fluctuation.

In finding intensity ratios of γ rays of different energies, calculated corrections were made for absorption in the gold lining (0.1 mm) and in an x-ray filter (1 mm of Cd and in some cases 3 mm of Pb) placed between target and detector. The calculations were checked for the two energies from a ^{24}Na source observed in the same geometry.

That observed γ rays of interest were, in fact, due to the ^{36}Ar was verified by similar runs with helium in the target cell.

III. EXPERIMENTAL RESULTS

Some properties of radioactive isotopes produced by bombardment of ^{36}Ar with ^{3}He at 11 MeV are listed in Table I. It may be seen that ^{38}Ca has a half-life distinctly different from all the others, so that its γ rays can be readily distinguished by proper choice of counting intervals.

Our results include four runs, two with each of the timing cycles given above. Figure 1 shows one of the pairs of delayed γ-ray spectra obtained with the shorter cycle, and Table II classifies the various transitions assigned to the observed γ rays. Tabulated intensities are normalized for each isotope to its predominant γ ray (ignoring annihilation radiation). In cases where delayed γ rays have been reported in the literature, but are not seen here, upper limits are given.

One γ ray has been assigned to the decay of ^{38}Ca. Its energy of 1568 keV permits attribution to the transition, $1695\rightarrow127$ keV, from the third excited level of ^{38}K to the metastable level at 127 keV. From the diminution of the γ-ray intensity in the second counting interval relative to the first, the decay half-life has been found to be $T_{1/2}=0.47\pm0.02$ sec (the mean of four independent runs).

Because of the complexity introduced by the many competing positron emitters created in the target, no attempt was made experimentally to determine the branching ratio for the new transition. However, the superallowed branch to the 0^+ state at 127 keV in ^{38}K may be calculated directly from the measured half-life of ^{38}Ca and the partial half-life already noted, viz., $r_{\beta_1^+}=(0.47\pm0.02)/(0.593\pm0.015)=0.79\pm0.04$. Then, in the absence of other competing transitions, the branch to the 1695-keV state is 0.21 ± 0.04. Table III summarizes the information acquired in this work on the decay of ^{38}Ca. Experimental upper limits listed for unobserved transitions to known excited states of ^{38}K were calculated from the γ-ray spectra by comparison with the intensity of the 1568-keV γ ray.

The values of γ-ray energies assigned in Table II to transitions in ^{34}S, following β^+ decay of ^{34}Cl^m, are in good agreement with values in the literature. However, there is some disagreement between the relative intensities reported here and previous values.[1] The data listed for ^{35}Cl and ^{37}Ar agree with earlier work.[1]

During the course of the search for ^{38}Ca γ rays, a peak in the γ-ray spectrum at 2914 ± 1 keV (No. 9″ in

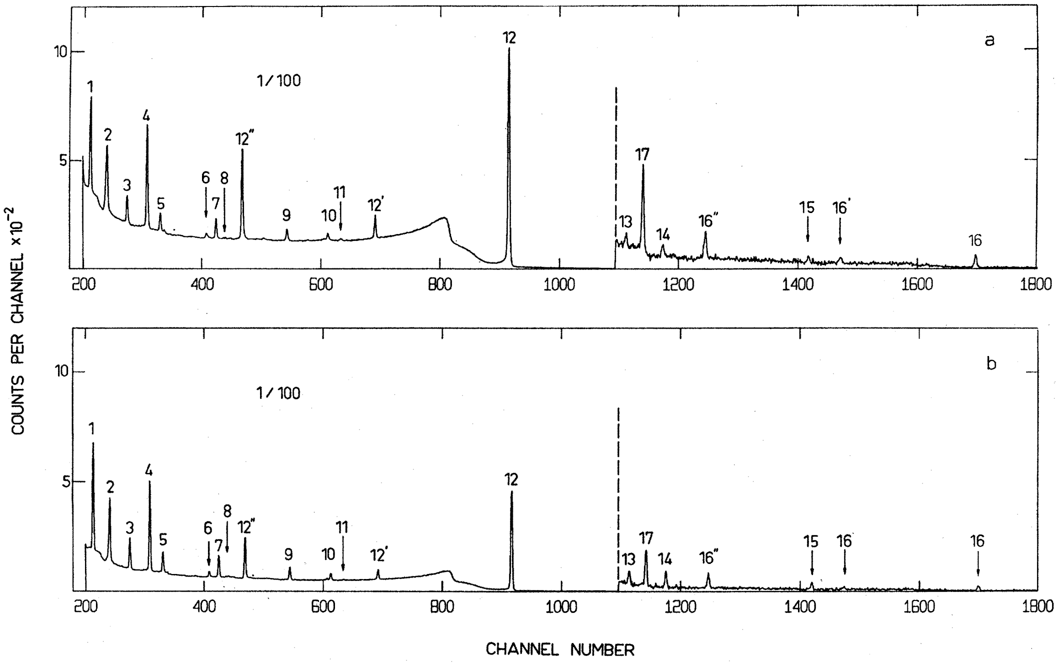

FIG. 2. Spectra of delayed γ rays in 22-cm^3 Ge(Li) after about 5-min activation of a thick KBr target by 11-MeV ^{3}He bombardment. Figures 2(a) and 2(b) are the spectra obtained in the first and second 10-min intervals after interception of the beam. Notation and normalization are as in Fig. 1. γ rays seen with energies 2168 and 3936 keV (lines 12 and 16), and also the sum peak, 2168+511 keV (line 17), have the same decay rate as, and are assigned to, the decay of 7.68-min ^{38}K. Line 11 (1526 keV) is due to ^{42}K$(\beta^-)^{42}$Ca activity, and line 13 (2614 keV) is from background thorium. Lines 15 (3303 keV) and 14 (2753 keV) are attributed to ^{34}Cl$^m(\beta^+)^{34}$S and ^{24}Na$(\beta^-)^{24}$Mg.

Fig. 1) was tentatively ascribed to a previously unreported β^+ transition from ^{38}K ($T_{1/2}=7.68$ min) to the fourth excited state of ^{38}Ar at 3936 keV. This interpretation was verified by subsequent experiments, similar in principle to the above, in which ^{38}K was formed, in the reaction ^{39}K(^{3}He,α), by 5-min irradiation of KI or KBr thick targets with a beam of 11-MeV ^{3}He. Then, two γ-ray spectra were accumulated in successive 10-min intervals, with results as illustrated in Fig. 2. Here the three peaks (No. 16, 16′, and 16″) due to the anticipated 3936-keV γ ray are clearly apparent, and from the intensity reduction in the second spectrum, the value $T_{1/2}=7.4\pm1.3$ min was found, confirming the assignment to ^{38}K decay. The results of the measurements are given in Table IV. It should be remarked that the β^+ branching was calculated assuming that the ^{38}Ar level at 3936 keV decays only to the ground state, as appears to be the case.[1]

The low-energy γ rays, numbered 1–10 in Fig. 2, are attributed to γ-ray transitions in ^{82}Kr following β^- and β^+ decays of ^{82}Br and ^{82}Rb^m, respectively,[6] produced by the reactions ^{81}Br(^{3}He,2p) and ^{81}Br(^{3}He,2n).

TABLE III. Results obtained for the β^+ radioactivity of ^{38}Ca.

$T_{1/2}$ (sec)	^{38}K* (MeV)	J^π,T	Branching ratio (%)	logft	E_γ (keV)
0.47±0.02	0.127	0$^+$,1	79±4	3.49±0.03	
	0.451		<3	>4.77	
	1.695	1$^+$,0	21±4	3.41±0.09	1567.7±0.5[a]
	2.40		<3	>3.84	
	3.6		<0.4	>3.86	

[a] Branching ratios for the γ-ray decay of the level at 1.695 MeV in ^{38}K have been found in the present work to be

$$r_{1.70\to0}<6,\quad r_{1.70\to0.13}=100,\quad r_{1.70\to0.45}<4.$$

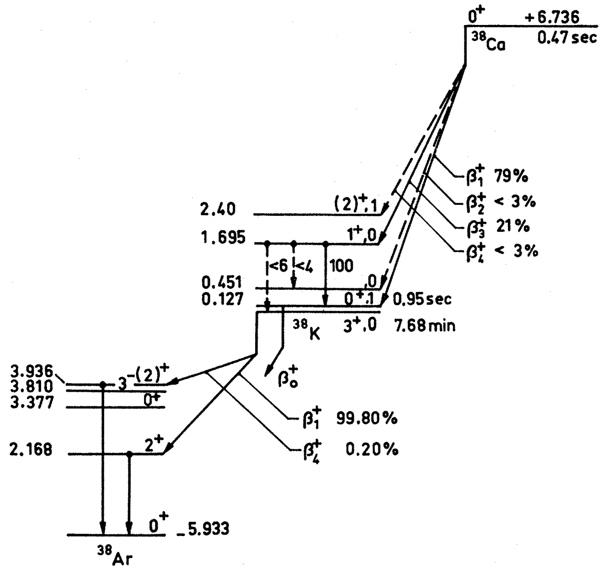

FIG. 3. The disintegration scheme of ^{38}Ca and ^{38}K incorporating the results of the present work.

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[6] Nuclear Data Sheets (ORNL), 1966, Sec. B (unpublished).

TABLE IV. Results obtained for the β^+ radioactivity of ^{38}K.

^{38}Ar* (MeV)	J^π	Branching ratio (%)	log ft	E_γ (keV) a	E_γ (keV) b
2.168	2^+	99.80±0.03	4.984±0.007	2167.5±0.3	2167.61±0.14
3.936	2^+	0.20±0.03	5.74 ±0.07	3935.6±0.5	3936. 1±0.5

[a] Values from the present work. [b] Values from Ref. 14.

IV. DISCUSSION AND CONCLUSIONS

The disintegration scheme for ^{38}Ca and ^{38}K, including results from the present work, is shown in Fig. 3. The energy levels and assignments shown are the results of numerous investigations. In ^{38}K, the β^+ decays of the ground state[7,8] and of the first excited state,[9] as well as the 0.95-sec half-life of the latter, have led to the assignments $(J^\pi,T)=(3^+,0)$ and $(0^+,1)$, respectively, to these levels. These attributions are consistent with the observations of Hashimoto and Alford[10] in a study of the reaction ^{40}Ca$(d,\alpha)^{38}$K. Further investigations of angular distributions and intensities from this reaction have led to suggestion of $(J^\pi,T)=(1^+,0)$ for both the second and third excited states (at 0.45 and 1.7 MeV excitation).[11–13] As already mentioned, still another 1^+ level at about 3.6 MeV is implied by the reported 3.5-MeV γ ray following ^{38}Ca decay.[2]

Of these three proposed 1^+ states, only one, that at 1.7 MeV, has been observed in the present work to be populated in ^{38}Ca decay. However, the observation of a γ transition from the 0.45-MeV level was greatly inhibited by the strong flux of annihilation radiation obscuring the relevant region. The limit found, $\log ft > 4.7$, is still within the range of values common for allowed transitions. Similarly, the measured limit, $\log ft > 3.86$, does not preclude the existence of a transition to a 1^+ state near 3.6-MeV excitation. However, the branching-ratio limit found here, $<0.4\%$, and the fact that the half-life used in the early report in support of such an assignment is substantially different from the present value, suggest that the observed 3.5-MeV γ ray may not be due to ^{38}Ca.

The existence of a strong transition from ^{38}Ca to the 1695-keV level of ^{38}K establishes $J^\pi=1^+$ for the level, and $T=0$ may be presumed from the well-known level structure of ^{38}Ar. The value of the reduced Gamow-Teller matrix element, $\|\int\sigma\|^2=0.54\pm0.11$, is large, but not exceptional in the $A=4N+2$ series of nuclei. Indeed, on the basis of a recently proposed approximate sum rule,[5] applicable for some simple two-particle (or hole) configurations with inert core, additional Gamow-Teller strength of at least 0.1 in $\|\int\sigma\|$ to other levels may be anticipated.

Since the spin matrix element is fairly large, an approximate estimate of the speed of the corresponding $M1$ γ-ray transition in ^{38}K, $1695\rightarrow127$ keV, may be made by ignoring the space part of the $M1$ matrix element.[5] The result, $\tau\approx10$ fsec, is near the lower limit of utility of the Doppler-shift attenuation method for measurement of γ-ray lifetimes.

Note added in proof. Dr. Engelbertink has kindly called to our attention that the lifetime of the $(3.936\rightarrow0)$-MeV transition in ^{38}Hr is 105±16 fsec.[14] This value, together with the allowed β^+ transition from ^{38}K, permits the firm assignment $J^\pi=2^+$ to the 3.936-MeV level.

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