The transition to the 2_1^+ level of Ca^{42} is about 50% more intense than the transition to 2_2^+ level. It is suggested that the transitions to the lowest six states do not exhaust the available $f_{7/2}$ strength. The spectroscopic factor for observed $l=0$ transitions in $Ca^{43}(d,t)Ca^{42}$ strongly suggests that the spectroscopic factor for this transition is significantly smaller than would be expected on the basis of the simple shell model. The $Ca^{48}(d,t)Ca^{47}$ result rules out the possibility of a small separation of the centroids of the $f_{7/2}^{-1}$ and $d_{3/2}^{-1}$ holes in Ca^{47}. The greatest part of the s^{-1} and $d_{3/2}^{-1}$ strength is found in the 2.60-MeV doublet. The $2p_{3/2}$-neutron admixture in the ground-state wave function of Ca^{48} is smaller than in those of Ca^{44} and Ca^{42}, but a significant $p_{1/2}$-neutron admixture was observed which did not appear present in the other two nuclei.

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Positron Decays of ^{42}Ti and ^{38}Ca

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The positron decay of ^{42}Ti has been investigated using the $^{40}Ca(h,n)$ reaction with a natural calcium target. A strong 610.7±0.5-keV γ ray with a half-life $T_{1/2}=0.202\pm0.005$ sec is attributed to a positron branch to the 611-keV level of ^{42}Sc. A weak 2222±2-keV γ ray has been observed, which corresponds to a positron branch to the 2223-keV level of ^{42}Sc. Using this measured half-life and the β-decay energies, the branching ratios are calculated from β-decay systematics to be $r_{\beta0}{}^+=(44.1\pm1.2)\%$, $r_{\beta1}{}^+=(55.2\pm1.2)\%$, and $r_{\beta9}{}^+=(0.7\pm0.3)\%$. The log*ft* values 3.179 ± 0.015 and $4.36_{-0.24}^{+0.16}$ establish $J^\pi=1^+$ for both the 611- and the 2223-keV states of ^{42}Sc. The positron decay of ^{38}Ca has been investigated using the $^{36}Ar(h,n)$ reaction. The half-life 0.439 ± 0.012 sec has been measured for this decay. In addition to the strong Gamow-Teller transition feeding the 1695-keV level of ^{38}K, a weak 3210±2-keV γ-ray line has been observed which is tentatively attributed to a transition from the 3337-keV level in ^{38}K fed by a $(0.6\pm0.2)\%$ β^+ branch of ^{38}Ca. Its log*ft* ($3.90_{-0.13}^{+0.10}$) then establishes the $J^\pi=1^+$ assignment for this state.

I. INTRODUCTION

The isotope ^{42}Ti has a mass 6983±8 keV greater than ^{42}Sc, and must therefore decay by superallowed β^+ emission to its isobaric analog ($J^\pi=0^+$, $T=1$) ground state of ^{42}Sc.[1,2] Using the above value for the total decay energy and the comparative half-life[3] for the superallowed 0^+ to 0^+ transitions, $ft=3123\pm31$ sec, one finds the corresponding half-life for ^{42}Ti to be 0.458±0.005 sec.

The first reported evidence for the β^+ decay of ^{42}Ti has been that of Oberholtzer,[4] who used the $^{40}Ca(h,n)$ reaction (the notation *h* for helion,[5] is used for ^{3}He) and observed, with a plastic scintillator, positrons with energy 6.0±0.6 MeV and a half-life of 0.25±0.04 sec, which he attributed to ^{42}Ti.

The present study of ^{42}Ti was undertaken to measure more accurately the half-life of ^{42}Ti and to search for γ rays following Gamow-Teller transitions from ^{42}Ti to $J^\pi=1^+$ states of the self-conjugate nucleus ^{42}Sc. Such strong transitions have already been observed in the $A=4N+2$ series of nuclei up to ^{30}P and in ^{38}Ca.[6-8]

The isotope ^{38}Ca decays by superallowed β^+ emission to its isobaric analog level ($J^\pi=0^+$, $T=1$) at an excitation of 127 keV and by a strong Gamow-Teller transition ($\log ft=3.41\pm0.09$) to the 1695-keV state in ^{38}K.[8] On the basis of a recently proposed sum rule[9] for the reduced matrix elements for the Gamow-Teller transitions in the $A=4N+2$ nuclei, one expects an additional strength of at least 0.1 in $||\int\sigma||^2$ to other levels in ^{38}K. The study of ^{38}Ca was undertaken to search for such additional transitions to $J^\pi=1^+$ states in ^{38}K.

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TABLE I. Delayed γ rays observed after 10.2-MeV helion bombardment of natural calcium.

Line No.[a]	E_γ(keV) Present work	Radioactivity	Transition	E_x(keV) final nucleus Present work	Ref. 2
1	437.5 ± 0.5	^{42}Sc^m β^+	^{42}Ca $3.190\rightarrow2.751$	3189.0 ± 0.9	3190 ± 6
8	1227.0 ± 0.5		$2.751\rightarrow1.524$	2751.5 ± 0.7	2751 ± 4
10	1524.5 ± 0.5		$1.524\rightarrow0$	1524.5 ± 0.5	1524.2 ± 1.1
3	610.7 ± 0.5	^{42}Ti β^+	^{42}Sc $0.611\rightarrow0$	610.7 ± 0.5	611.5 ± 0.5[b]
17	2222 ± 2		$2.223\rightarrow0$	2222 ± 2	2223.0 ± 0.9[b]
7	1155.8 ± 1.0	^{44}Sc β^+ ^{44}Sc^m β^+	^{44}Ca $1.156\rightarrow0$	1155.8 ± 1.0	1156.1 ± 1.0
16	2167.6 ± 0.5	^{38}K β^+	^{38}Ar $2.168\rightarrow0$	2167.7 ± 0.5	2167.61 ± 0.14

[a] The numbering is that used for the peaks in Figs. 1 and 2.

[b] Reference 14.

II. EXPERIMENTAL METHOD

The isotope ^{42}Ti was produced in the reaction ^{40}Ca(h, n), using the ^{3}He^{2+} beam from the 5.5-MV Van de Graaff at Strasbourg at bombarding energies of 10.0 to 11.0 MeV. Natural calcium targets with thicknesses ranging from 1 to 2 mg/cm^2 were prepared by vacuum evaporation onto tantalum, and protected from oxydation by the further evaporation of a 300 μg/cm^2 layer of gold. The energy loss of the beam in gold was about 45 keV.

The isotope ^{38}Ca was produced in the reaction ^{36}Ar(h, n), using a 10.2-MeV ^{3}He^{2+} beam and a gas target enriched to $>99.9\%$ ^{36}Ar.[8]

γ rays were observed at 90°, with Ge(Li) detectors of 46 and 62 cm^3, having a resolution of about 4.0 keV for the 1.33-MeV ^{60}Co γ rays, at the count rates used.

The study of delayed γ rays was performed using a stable electronic-sequence timer[8,10] to program the activation-measurement cycle, which consisted of bombardment for a time t_0, and the storage of two successive spectra during t_1 and t_2 in separate halves of a 4096-channel analyser. The storage was started about 100 msec after the magnetic deflection of the beam onto a remote tantalum plate. The set of times (t_0, t_1, t_2) was adjustable to facilitate the identification of γ rays, based on their decay, observed during t_1 and t_2. The half-life of the decay could also be determined from the ratio of counts observed for a γ ray peak in the two successive spectra.

To reduce the errors in half-life determinations, the number of successive spectra has been increased from two to four. The activation-measurement cycles described above were combined with a precision timing unit (quartz oscillator) and a fast routing circuit allowing four successive spectra of 1024 channels to be stored in separate regions of the multichannel analyser. In that way, a much higher accuracy could be reached for the half-life determination, without considerable increase in the duration of the measurement. Observed timing drifts were negligible, but correction of the intensity ratios 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. Beam fluctuations caused an error in the dead-time correction which was estimated to be $<1\%$.

For ^{42}Ti, two different cycles (t_0, t_1, t_2) were used for the two-point measurements: 244, 320, and 372 msec and 210, 300, and 347 msec. For the half-life measurements, the bombardment time was $t_0=242$ msec, each of the four successive spectra being measured for 200 msec.

For ^{38}Ca, the cycle 400, 624, and 603 msec was used for the two-point measurements. For the half-life measurements, the bombarding time was $t_0=505$ msec, each of the four successive spectra being measured for 400 msec.

For some measurements on ^{42}Ti to search for weak γ rays situated on strong Compton distributions, a three-crystal spectrometer with a Ge(Li) as primary detector was used. It consisted of a 24-cm^3 Ge(Li) detector surrounded by two large (6×3 in.) NaI(Tl) crystals, each having a $1\frac{1}{8}$-in.-radius semicircular slot cut in its face, to facilitate the positioning of the Ge(Li) detector. The spectrometer could be operated simultaneously in the direct, pair-spectrometer, and Compton-suppression modes.

To find the intensity ratios of γ rays of different energies, an experimental efficiency curve was developed using the well-known radioactive sources of ^{22}Na, ^{60}Co, ^{88}Y, ^{56}Co, ^{38}Cl, and ^{24}Na. The absorption in an x-ray filter (lead and cadmium) placed between the target and the detector was also taken into account. The energy calibration of the γ-ray spectra was found with the radioactive sources mentioned above.

That the observed γ rays of interest were in fact due to reactions on the target was verified in the case of ^{42}Ti by the helion bombardment of a 300-μg/cm^2 gold target on tantalum, and in the case of ^{38}Ca by similar runs with helium in the gas-target cell.

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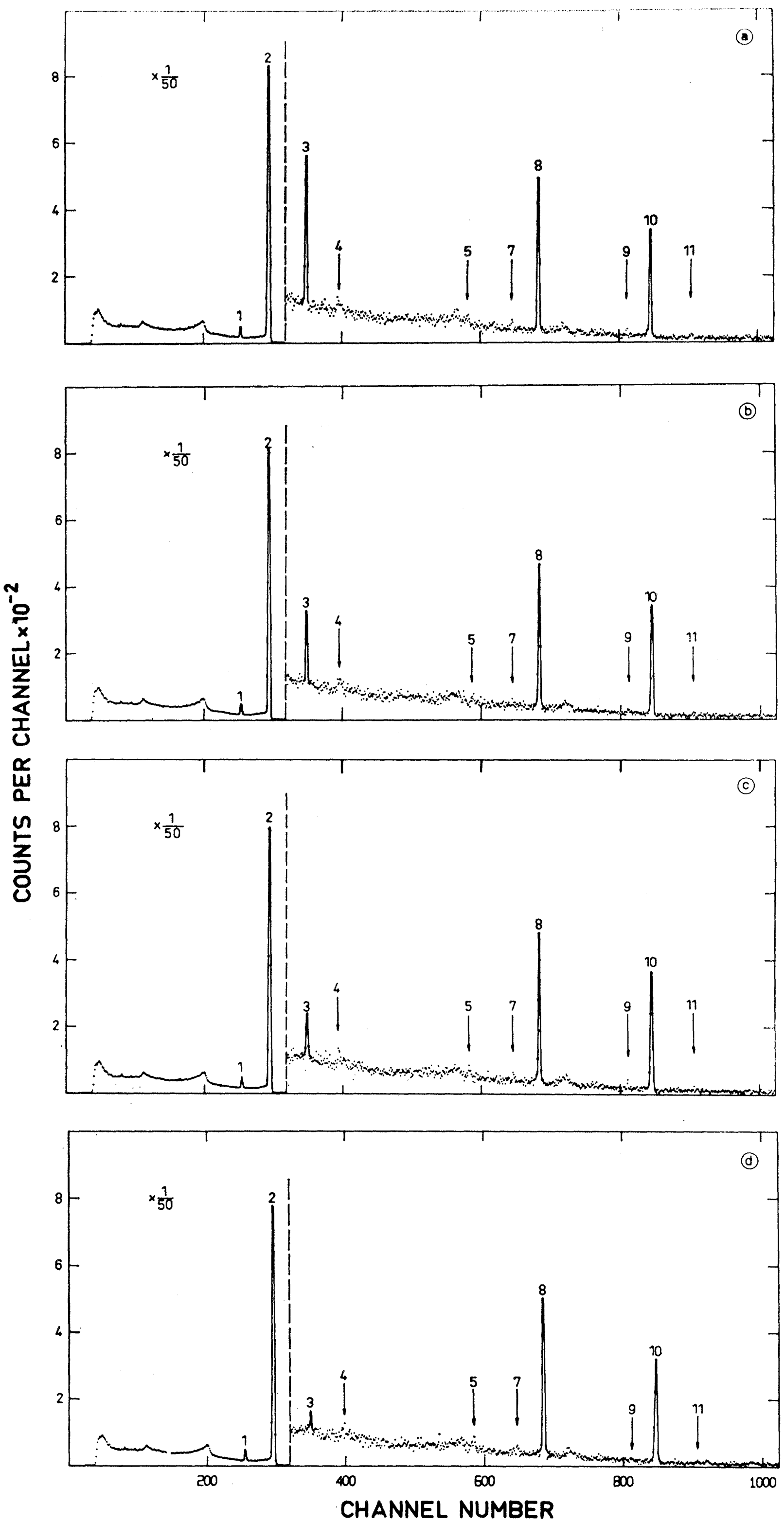

FIG. 1. Spectra of delayed γ rays observed with the three-crystal spectrometer after 10-MeV helion bombardment of natural calcium. The spectra were measured 98 msec after the end of a beam burst (243 msec), for successive intervals of 200 msec. The short lifetime of the 611-keV γ ray (line 3), due to ^{42}Ti, is readily seen. Line 2 is due to the annihilation radiation, and line 4 to the well-known decay of ^{72m}Ge. Lines 5 (1043 keV) and 11 (1632 keV) are due to the β decays of ^{18}Ne and ^{20}F, respectively. The 1460-keV γ rays (line 9) were due to the background ^{40}K activity. For other transitions, see Table I.

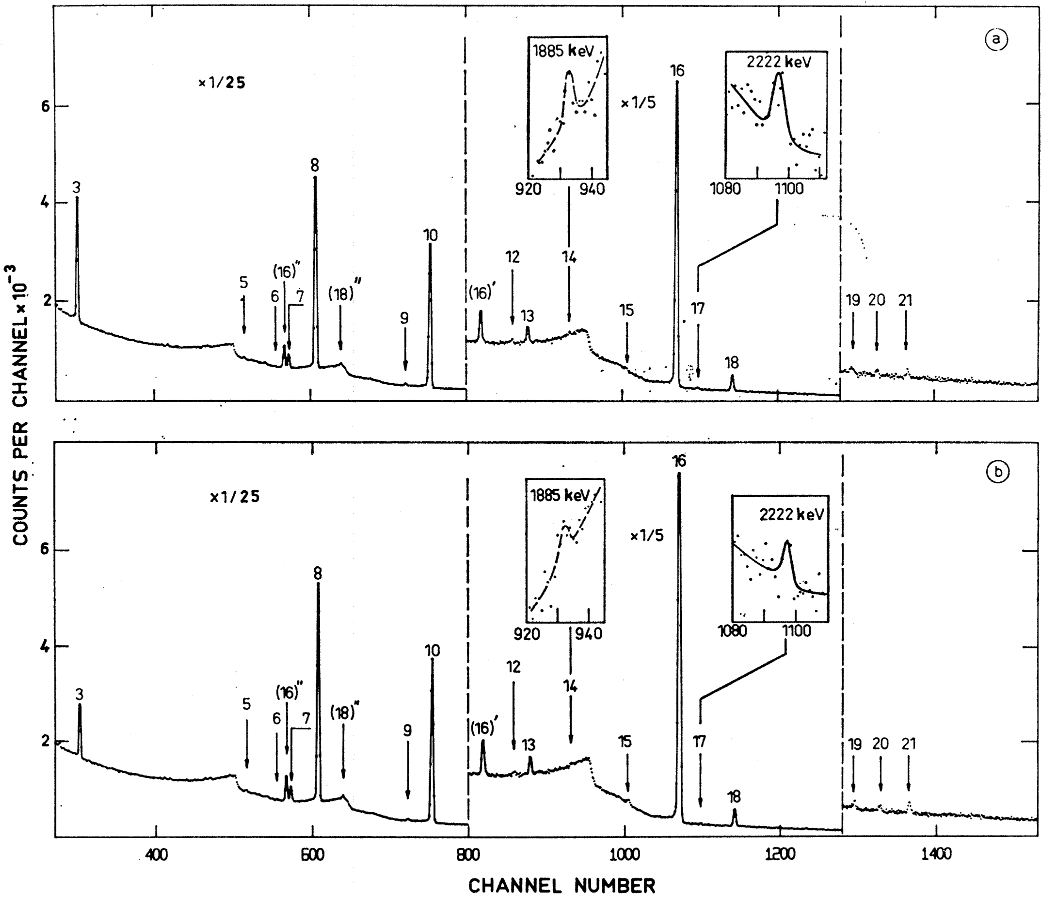

FIG. 2. Spectra of delayed γ rays observed with a 46-cm^3 Ge(Li) after 10.2-MeV helion bombardment of natural calcium. Figure 2(a) is the spectrum observed in the interval 95–395 msec after the end of the irradiation (210 msec), and Fig. 2(b) that observed in the next 347 msec. One- and two-escape peaks arising from a given γ ray are distinguished by one and two primes, respectively. The short lifetime of the 611- and 2222-keV γ rays (lines 3 and 17), due to ^{42}Ti, can be easily distinguished. Line 6 (1120 keV) is due to the β^- decay of ^{46}Sc produced by the ^{44}Ca(^3h, p) reaction. Lines 13 (1776 keV), 18 (2312 keV), and 19 (2614 keV) are due to the activities of ^{28}Al, ^{14}O and background thorium, respectively. Lines 12, 15, 20, and 21 are attributed to the sum peaks (1227+511), (1524+511), (2168+511), and (1227+1524) keV. For other transitions, see Table I, the caption of Fig. 1, and the text.

III. EXPERIMENTAL RESULTS

^{42}Ti

The properties of the radioactive isotopes other than ^{42}Ti, produced by the helion bombardment of a natural calcium target, are distinctly different from those of ^{42}Ti, so that its γ rays can be readily distinguished by the proper choice of the counting intervals.

Our results include six runs of two-point measurements and three runs of four-point measurements for the half-life determination. Figure 1 shows four delayed γ-ray spectra of a half-life measurement, using the three-crystal spectrometer in the Compton-suppression mode. Figure 2 shows one of the pairs of delayed γ-ray spectra obtained with the 46-cm^3 Ge(Li) detector. Table I classifies the various transitions assigned to the observed γ rays.

A strong 610.7±0.5-keV γ ray has been attributed to the 611→0 keV transition from the first excited state of

TABLE II. Results obtained for the β^+ radioactivity of ^{42}Ti.

$T_{1/2}$ (sec)	^{42}Sc (MeV)	J^π, T	Branching ratio (%)	logft	E_γ (keV)
0.202±0.005	0	0^+, 1	44.1±1.2	3.494±0.016	
	0.611	1^+, 0	55.2±1.2	3.179±0.015	610.7±0.5
	1.88		≤1.2	≥4.38	(1885±2)
	2.223	1^+, 0	0.7±0.3[a]	$4.36_{-0.24}^{+0.16}$	2222±2

[a] Value obtained in considering only the 2.223→0 γ-ray transition for the decay of the 2.223-MeV state.

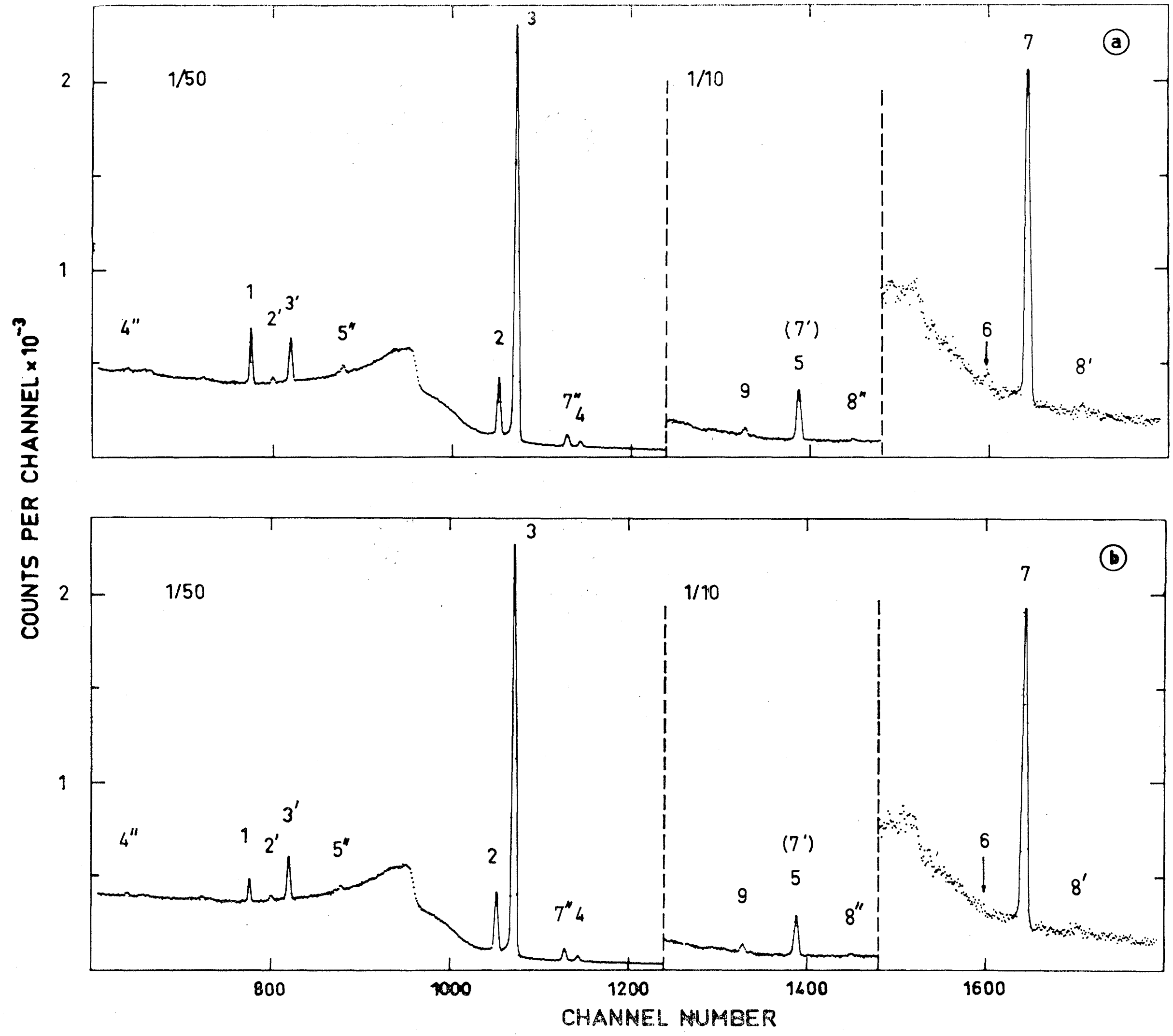

FIG. 3. Spectra of delayed γ rays observed with a 46-cm^3 Ge(Li) after 10.2-MeV helion bombardment of ^{36}Ar. Figure 3(a) is the spectrum observed in the interval 100–724 msec after the end of the beam burst (400 msec), and Fig. 3(b) that observed in the next 603 msec. The rapid decrease in intensity of the 1568- and 3210-keV γ rays (lines 1 and 6), due to ^{38}Ca, can readily be seen. Lines 2 (2127 keV) and 7 (3303 keV) are due to ^{34m}Cl. Line 3 (2167 keV) is due to ^{38}K and so are the one- and two-escape peaks (lines 8′ and 8″) of the 3936-keV γ rays. The 2794-keV γ rays (line 5) are attributed to ^{37}K and the 2312-keV γ rays (line 4) to ^{14}O. Line 9 is due to the sum peak 2168+511 keV.

^{42}Sc following the decay of ^{42}Ti. From the decrease of the γ-ray intensity in the four successive counting intervals, the decay half-life has been found to be $T_{1/2}=0.202\pm0.005$ sec.

During a long run of a two-point measurement, evidence was found for a weak 2222±2-keV full-energy peak, decaying with a half-life of 0.22±0.11 sec. In spite of its large statistical error, this value excludes other short-lived β activities which could have been produced in the experiment, and therefore allows the assignment of the 2222-keV γ ray to the 2223 keV→0 transition in ^{42}Sc, fed in the ^{42}Ti-decay.

Some evidence has also been found for the decay in intensity of a weak 1885±2-keV γ ray (line 14, Fig. 2). However, because of the presence of the strong Compton distribution of the 2168-keV γ rays, its intensity ratio in the two spectra could not be determined accurately, and therefore no definite attribution of this transition to ^{42}Ti could be made.

Because of the complexity introduced by the many competing positron emitters created in the target, no attempt was made to determine the β branching ratios experimentally, that is, by decomposing the intensity of the annihilation radiation.[6,7] However, the branching ratio of the superallowed branch of ^{42}Ti to the 0^+ ground state of ^{42}Sc may be calculated directly from the measured half-life and the partial half-life already noted: $r_{\beta_0^+}=(0.202\pm0.005)/(0.458\pm0.005)=0.441\pm$

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)
0.439 ± 0.012	0.127	0^+, 1	74 ± 4	3.49 ± 0.03	
	0.451		<3	>4.77	
	1.695[a]	1^+, 0	25.4 ± 4.0	$3.30_{-0.08}^{+0.07}$	1567.7 ± 0.5[b]
	(3.337)	(1^+, 0)	(0.6 ± 0.2)	($3.90_{-0.13}^{+0.10}$)	3210 ± 2[c]

[a] Branching ratios for the γ-ray decay of the level at 1.694 MeV in ^{38}K have been found in the present work to be $r_{1.695\to0}<2$, $r_{1.695\to0.127}=100$, and $r_{1.695\to0.451}<2$.

[b] Value from the earlier work, Ref. 8.

[c] An upper limit of 50% can be estimated for other competing decay modes of this level.

0.012. Thus, the branching ratio of all other possible transitions of ^{42}Ti to ^{42}Sc is 0.559 ± 0.012. In the absence of other competing transitions, the relative intensities of the 611- and 2222-keV γ rays, calculated to be 100 and 1.2 ± 0.4, determine the branching ratios 0.552 ± 0.012 and $(7\pm3)\times10^{-3}$ for the transitions of ^{42}Ti to the 611- and 2223-keV states in ^{42}Sc, respectively. Table II summarizes the information acquired in this work on the decay of ^{42}Ti.

The values of γ-ray energies assigned in Table I to transitions in ^{42}Ca following the β^+ decay of ^{42m}Sc, are more precise than, and in good agreement with, earlier reported values.[2]

^{38}Ca

The half-life measurements on ^{38}Ca were based on the decay of the 1568-keV γ ray, due to the 1695→127-keV transition in ^{38}K following the β^+ decay of ^{38}Ca.[8] The value of the half-life determined in this way is 0.439 ± 0.012 sec.

Figure 3 shows the result of a two-point measurement. In the presence of all γ transitions observed in the earlier work[8] on ^{38}Ca, a weak full-energy peak of 3210 ± 2 keV (line 6) has been observed with a rapid decay in intensity. Taking into account the intensity of this line in the first spectrum and its upper limit in the second, we find an upper limit for its half-life of 0.45 sec. Considering all possible reactions produced in the target, this limit allows the attribution of the 3210-keV line to the 3337→127-keV transition in ^{38}K, fed in the β^+ decay of ^{38}Ca. The excitation energy of 3337 ± 6 keV for the corresponding ^{38}K level is in agreement with the value 3.33 ± 0.02 MeV.[2] Nevertheless, it must be pointed out that no lower limit could be set for the decay of the 3210-keV γ ray. The possible assignment of this γ ray to an isotope with a half-life $T_{1/2}\ll0.45$ sec can not be definitely excluded.

The branching ratio $r_{\beta_1^+}=0.74\pm0.04$ of the superallowed transition of ^{38}Ca to the 127-keV state of ^{38}K has been calculated from the measured half-life of ^{38}Ca, 0.439 ± 0.012 sec, and the partial half-life, 0.597 ± 0.015 sec.[8] The branching ratio for all other possible transitions of ^{38}Ca to ^{38}K is then 0.26 ± 0.04. In the absence of other competing transitions, the relative intensities of the 1568- and 3210-keV γ rays, calculated to be 100 and 2.3 ± 0.5, determine the β^+ branching ratios 0.254 ± 0.040 and $(6\pm2)\times10^{-3}$ for the transitions of ^{38}Ca to the 1695- and 3337-keV states in ^{38}K, respectively. Table III summarizes the information acquired in this work on the decay of ^{38}Ca.

IV. DISCUSSION AND CONCLUSIONS

^{42}Ti

The disintegration scheme for ^{42}Ti including results from the present work is shown in Fig. 4. The existence of the allowed transitions to the 611- and 2223-keV levels of ^{42}Sc establishes $J^\pi=1^+$ for both levels, and $T=0$ may be presumed from other work reported in the literature.[2] The values of the reduced Gamow-Teller matrix elements for these transitions are $\|\int\sigma\|^2=0.91\pm0.04$ and 0.060 ± 0.027, respectively.

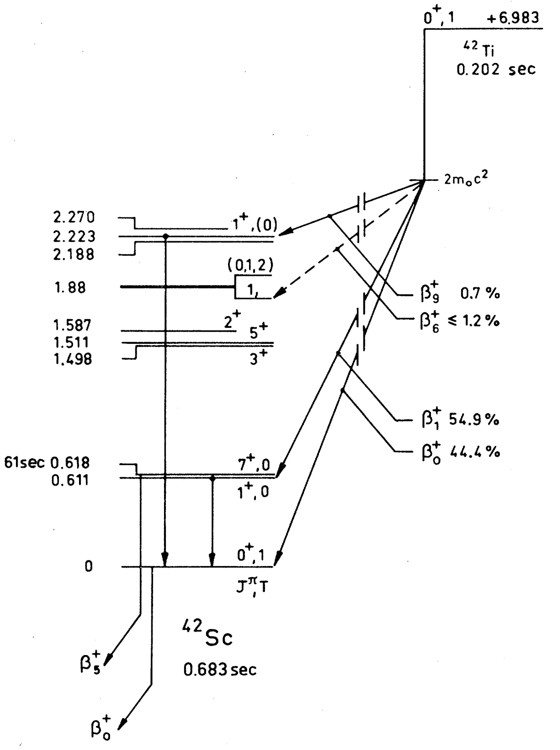

FIG. 4. The disintegration scheme of ^{42}Ti, incorporating the results of the present work.

Since the spin-matrix element in the case of the transition to the 611-keV level is fairly large, an approximate estimate of the speed of the corresponding $M1$ γ-ray transition in ^{42}Sc may be made by ignoring the space part of the $M1$ matrix element. We then find $\tau \simeq 1.0 \times 10^{-13}$ sec for the lifetime of the 611-keV level.

Many excited states of ^{42}Sc and ^{42}Ca have been found[2,11–14] which are not explained by the $(f_{7/2})^2$ configuration spectrum with a ^{40}Ca inert core. This suggests the presence of other two-particle configurations,[13] $(f_{7/2})^3$ $(d_{3/2})^{-1}$ configurations,[15] and also deformed four-particle–two-hole states.[16,17] During the preparation of this paper, we learned about the recent work of Nicholas *et al.*,[14] who studied ^{42}Sc using the ^{40}Ca$(h, p\,\gamma)$ reaction, through p-γ angular-correlation measurements. In particular, evidence has been found for a doublet of states at the energy of the earlier reported[12] 1.88-MeV, $J^\pi = 0^+$ level in ^{42}Sc, and the spin $J=1$ has been assigned to one member of this doublet. The spin $J=1$ has also been assigned to the 611- and 2223-keV levels of ^{42}Sc.

The present work on the β^+ decay of ^{42}Ti establishes a $J^\pi = 1^+$ assignment for the 611- and 2223-keV states of ^{42}Sc, in agreement with the above study.[14] Our limit on the branching ratio for a β^+ transition to one member of the 1.88-MeV doublet does not exclude the $J=1$ assignment to this level.

Our value of 0.202±0.005 sec for the half-life of ^{42}Ti is in good agreement with the value of 0.20±0.02 sec,[14] but is in disagreement with the recently reported[18] value of 0.29 sec.

^{38}Ca

The new value, 0.439±0.012 sec, for the half-life of ^{38}Ca modifies only slightly the results of the earlier reported work.[8]

In addition to the Gamow-Teller transition to the 1695-keV 1^+, $T=0$ level of ^{38}K, another transition of this type, $\log ft = 3.90_{-0.13}^{+0.10}$ has been observed to the 3337-keV level of ^{38}K, which has, therefore, $J^\pi = 1^+$. The $T=0$ assignment can be deduced from earlier reported studies of ^{38}K using the ^{40}Ca(d, α) reaction.[19,20]

The values of the reduced Gamow-Teller matrix elements $|| \int \sigma ||^2 = 0.70 \pm 0.12$ and 0.17 ± 0.05 have been deduced for the transitions to the 1695- and 3337-keV states of ^{38}K, respectively. The large value of the spin-matrix element, for the first of these transitions, permits an estimation of the speed of the corresponding $M1$ 1695→127-keV transition in ^{38}K. In this way, the lifetime $\tau \simeq 8$ fsec has been obtained for the 1695-keV level of ^{38}K.

In the present work, no evidence could be found for a transition of ^{38}Ca to the proposed (1^+, $T=0$) 450-keV level of ^{38}K.[19,20]

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