PHYSICAL REVIEW C VOLUME 2, NUMBER 4 OCTOBER 1970

Beta Decay of K^{47}, Ca^{50}, and Sc^{50}†

E. K. Warburton, D. E. Alburger, and G. A. P. Engelbertink
Brookhaven National Laboratory, Upton, New York 11973

(Received 1 June 1970)

The isotopes K^{47}, Ca^{50}, and Sc^{50} were formed by the bombardment of Ca^{48} with 3.3-MeV tritons. Half-lives of 18.1 ± 1.0, 13.9 ± 0.6, and 102.5 ± 0.5 sec, respectively, were measured by following the decay of the γ rays emitted by these nuclides. The γ rays were observed with a Ge(Li) detector, and γ-ray energies and relative intensities were obtained. K^{47} decays to the second and third excited states of Ca^{47}; Ca^{50} to the fourth excited state of Sc^{50}; and Sc^{50} to the second and third excited states of Ti^{50}. The results for K^{47}, together with previous results, establish the spin-parity of the 2578- and 2599-keV levels of Ca^{47} as $\frac{3}{2}^+$ and $\frac{1}{2}^+$, respectively. The results for Sc^{50} and Ca^{50} are consistent with previous work, but are more accurate.

I. INTRODUCTION

When Ca^{48} is bombarded with 3-MeV tritons the radioisotopes K^{47}, Ca^{50}, and Sc^{50} are produced via the reactions $Ca^{48}(t,\alpha)K^{47}$ ($Q = 4.006$ MeV), $Ca^{48}(t,p)Ca^{50}$ ($Q = 3.017$ MeV), and $Ca^{48}(t,n)Sc^{50}$ ($Q = 7.002$ MeV). Sc^{50} is also produced by $Ca^{50}(\beta^-)Sc^{50}$. Reported herein is a study of these activities produced via $Ca^{48}+t$.

The β^- emitter K^{47} was first found and studied via the $Ca^{48}(\gamma,p)K^{47}$ reaction.[1] It was observed to decay with a half-life of 17.5 ± 0.3 sec to the first excited state at 2.01 MeV (85%) and to the second excited state at 2.6 MeV (15%) with log*ft* values of 4.8 and 5.4, respectively. Since both these log*ft* values fall in the allowed region[2] it was concluded that the K^{47} ground state and the Ca^{47} 2.01- and 2.6-MeV levels have the same parity. Subsequently, it has been established that the Ca^{47} 2.01-MeV level[3] has $J^\pi = \frac{3}{2}^-$, and the K^{47} ground state has[4] $J^\pi = \frac{1}{2}^+$; while the 2.6-MeV level of Ca^{47} is actually a doublet with excitation energies of 2580 ± 5 and 2601 ± 5 keV and spin-parity assignments[3] of $(\frac{3}{2}^+, \frac{5}{2}^+)$ and $\frac{1}{2}^+$, respectively. These findings are obviously in conflict with the K^{47} decay results of Kuroyanagi *et al.*[1] and so a reinvestigation of the β^- decay of K^{47} is in order.

The β^- decay of Ca^{50} has been most recently and thoroughly studied by Chase, McDonald, and Nightingale (CMN)[5] who observed that the decay proceeded to the 1848-keV fourth excited state of Sc^{50} rather than to the second excited state at 329 keV as had been first proposed.[6] Half-lives of 14 ± 3 sec[5] and 9 ± 2 sec[6] have been reported. It was our intention to check the results of CMN and to provide more accurate energy measurements for the Sc^{50} γ rays and a more accurate half-life for Ca^{50}.

Sc^{50} has a half-life[3] of 103.8 ± 1.7 sec and decays predominantly to the Ti^{50} 3.20-MeV third excited state. There is evidence[7] for a small branch [(15 ± 7)%] to the 2.68-MeV level, but other investigations[3] yield somewhat smaller, albeit even less well defined, values for this branch. It was our intention to determine more accurate energies for the Ti^{50} γ rays and more accurate branching ratios for the decay of Sc^{50} to the 2.68- and 3.20-MeV levels of Ti^{50}.

II. EXPERIMENTAL PROCEDURE AND RESULTS

A. $Sc^{50}(\beta^-)Ti^{50}$

A 30-cc Ge(Li) detector system with an energy resolution defined by a full width at half maximum (FWHM) of 2.1 keV for the Co^{60} lines was used for investigation of the delayed γ rays from $Ca^{48}+t$. The Ca^{48} target consisted of a 250-mg CaF_2 crystal with the Ca enriched to 96.6% in Ca^{48}. The CaF_2 was approximately in the form of a cylinder 1 cm in diameter and thick enough to stop the beam.[8,9] The triton beam was provided by the BNL 3.5-MeV Van de Graaff accelerator.

The 1.7-min Sc^{50} activity was investigated first. The main problem was to obtain an accurate relative-intensity measurement of the three Ti^{50} γ rays observed[3,5-7] in the β^- decay of Sc^{50}. A relative-efficiency curve accurate to $\leq 2\%$ had already been determined for γ-ray photopeaks observed with the 30-cc Ge (Li) detector.[10] Thus, γ-ray spectra were recorded under the same conditions as used in the determination of this curve (a source-to-detector-face distance of ~6 cm with no material between the detector housing and source).

The Ca^{48} was placed under vacuum and bombarded for 2 min with a 20-nA 3.3-MeV triton beam. It was then removed from the target chamber, carried to the shielded Ge(Li) detector situated in another room, and counted for 3 min after a 1.5-min wait. This procedure was repeated 12 times. The pertinent portion of the resulting Ge(Li) spectrum is shown in Fig. 1. The whole procedure was repeated once under different conditions of energy dispersion, counting rate, etc. The two spectra

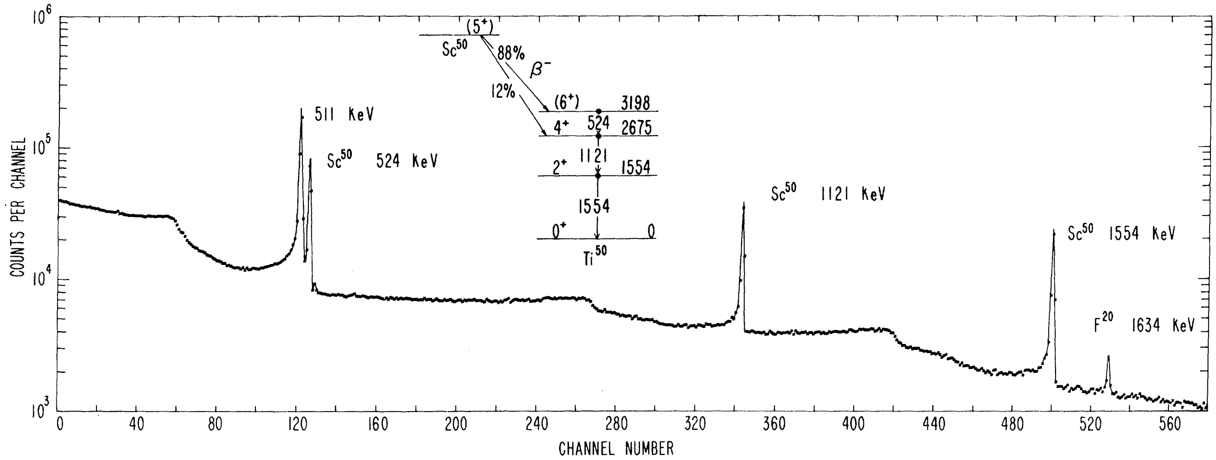

FIG. 1. 30-cc Ge(Li) γ-ray spectrum observed following bombardment of $Ca^{48}F_2$ with a 3.3-MeV triton beam. The original spectrum has been compressed by a factor of 3 to facilitate display. The spectrum shown is the sum of 12 cycles consisting of 2-min bombardment at 20 nA, 1.5-min wait, and 3-min counting. The three lines ascribed to the decay of Sc^{50} are indicated. The F^{20} γ ray is due to $F^{19}(t,d)F^{20}(\beta^-)Ne^{20}(1 \rightarrow 0)$. F^{20} has $T_{1/2} = 11$ sec. The insert shows the origin of the three Sc^{50} γ rays.

were analyzed to obtain relative intensities for the three Sc^{50} γ rays indicated in Fig. 1. The two results were in good agreement yielding intensities for the 524- and 1554-keV lines, relative to 100 for the 1121-keV line, of 88 ± 3 and 102 ± 3. The intensity of the 524-keV line is definitely less than that of the 1121-keV line so that there is a branch to the 4^+, 2.68-MeV level as well as to the (6^+), 3.20-MeV level as indicated in the insert of Fig. 1 and in Table I. Our result for the branch to the 2.68-MeV level [(12 ± 3)%] is in excellent agreement with the value of (15 ± 7)% found by Chilosi *et al.*[7]

A search for other γ rays from $Sc^{50}(\beta^-)Ti^{50}$ was undertaken with 2.5 cm of Lucite inserted between the source and detector in order to stop electrons emanating from the source. This shielding decreased the background significantly, especially in the energy region above the 1554-keV γ-ray full-energy peak. The main source of background for $E_\gamma > 1554$ keV was the 8.8-min Ca^{49} activity,[11] produced via the $Ca^{48}(t,d)Ca^{49}$ reaction ($Q = -1.113$ MeV). No other γ rays were observed that could be ascribed to a 1.7-min activity. We can say that the intensity of any such γ rays with $E_\gamma > 530$ keV is less than 1% of the intensity of the 524-keV γ ray.

Accurate energies were obtained for the three Sc^{50} γ rays of Fig. 1 from a 4096-channel spectrum taken with mixed sources of Sc^{50}, Co^{60}, ThC'', F^{20}, Ca^{49}, and Bi^{207}. The peak positions were determined by Gaussian fits, and a least-squares fit to

$$E = \sum_{n=0}^{m} a_n x^n$$

was made to the γ rays of known energy, where x is the channel number and m is varied from 1 to 4. Four such spectra were taken and analyzed. In all cases the quality of the calibration improved

TABLE I. Half-lives, branching ratios, and log*ft* values for the β^- decays of K^{47}, Ca^{50}, and Sc^{50}.

Transition	Half-life (sec)	Branching ratio (%)	E_β(max) (Ref. a) (keV)	log*ft*	Conclusion
$K^{47}(\beta^-)Ca^{47}(1)$	17.5 ± 0.3	<9.0 [b]	4637 ± 13	>6.03	...
$K^{47}(\beta^-)Ca^{47}(2)$		14.6 ± 1.5	4072 ± 13	5.57 ± 0.05	allowed
$K^{47}(\beta^-)Ca^{47}(3)$		85.4 ± 5.0	4051 ± 13	4.79 ± 0.03	allowed
$Ca^{50}(\beta^-)Sc^{50}(4)$	13.9 ± 0.6	100.0	3118 ± 17	4.13 ± 0.02	allowed
$Sc^{50}(\beta^-)Ti^{50}(1)$	102.5 ± 0.5	<5.0 [b]	5336 ± 20	>7.36	...
$Sc^{50}(\beta^-)Ti^{50}(2)$		12.0 ± 3.0 [c]	4215 ± 20	6.51 ± 0.11	$\lvert\Delta J\rvert \leq 1$
$Sc^{50}(\beta^-)Ti^{50}(3)$		88.0 ± 3.0 [c]	3692 ± 20	5.39 ± 0.02	allowed

[a] From the present excitation energies and previous ground-state energy differences (see Ref. 3).

[b] This branch was assumed to be zero in the calculation of other branching ratios and log*ft* values.

[c] *Note added in proof:* These branching ratios are in serious disagreement with recently obtained values of (24 ± 1)% and (76 ± 2)% [T. E. Ward and P. K. Kuvoda, Radiochim. Acta. 12, 217 (1969)].

drastically (i.e., χ^2 decreased markedly) when m was increased from 2 to 3. This reflects the presence of monotonically varying nonlinearities in the detector-amplifier-analyzer system.[12] Our Sc^{50} γ-ray energies were taken from the calibration curve with $m=3$; the results are given in Table II, and the resulting excitation energies are listed in Table III.

The half-life of Sc^{50} was measured using a 5×6-in. NaI(Tl) γ-ray detector to view γ rays from the source. The NaI(Tl) detector was shielded on the sides with Pb and had 2.5 cm of Lucite over its front face. An energy gate was set on the 1121-keV full-energy peak (Fig. 1), and the time decay of the γ-ray counts in this gate was observed using a Northern Scientific Inc. 4096-channel analyzer operating in a time scaling mode ("multiscaling") with 0.9 sec/channel. The decay was followed for 20 min after a 2-min bombardment and a 1-min wait. This procedure was repeated twice. The long-lived ($T_{1/2}\gg1$ min) background, mostly from the 8.8-min Ca^{49} activity, was 0.6% of the initial Sc^{50} counting rate and thus introduced negligible error when taken into account. The half-life was extracted using several different computer fitting procedures and programs developed in a comprehensive study of $\beta^{\pm}$ half-lives.[13] The result was 102.5 ± 0.5 sec, where the uncertainty is mainly an estimate of the systematic errors – the statistical error being ±0.2 sec. This result is in good agreement with the average[3] of previous values, 103.8 ± 1.7 sec.

B. $\mathrm{Ca}^{50}(\beta^-)\mathrm{Sc}^{50}$

The study of the decay of both Ca^{50} and K^{47} was made using a pneumatic beam shutter about 5-m upstream from the Ca^{48} target. A cam system allowed continuous cycling with a 20-sec irradiation and a 80-sec counting period. A TMC 16384-channel analyzer was programmed to record four sequential 4096-channel spectra, each of 18-sec duration, during the 80-sec counting period. The 30-cc Ge(Li) detector viewed the target *in situ* and was well shielded against the Van de Graaff accelerator by lead. The intensity of the 3.3-MeV triton beam was 60 nA throughout.

TABLE II. Energies and assignments of γ rays from activities produced by $\mathrm{Ca}^{48}+t$.

E_γ (keV)	Assignment	Source
71.54 ± 0.20	Sc^{50} $2\to1$	$\mathrm{Ca}^{50}(\beta^-)$
256.94 ± 0.10	Sc^{50} $1\to0$	$\mathrm{Ca}^{50}(\beta^-)$
523.50 ± 0.10	Ti^{50} $3\to2$	$\mathrm{Sc}^{50}(\beta^-)$
564.74 ± 0.30	Ca^{47} $2\to1$	$\mathrm{K}^{47}(\beta^-)$
585.75 ± 0.30	Ca^{47} $3\to1$	$\mathrm{K}^{47}(\beta^-)$
1121.03 ± 0.10	Ti^{50} $2\to1$	$\mathrm{Sc}^{50}(\beta^-)$
1519.44 ± 0.30	Sc^{50} $4\to2$	$\mathrm{Ca}^{50}(\beta^-)$
1553.71 ± 0.20	Ti^{50} $1\to0$	$\mathrm{Sc}^{50}(\beta^-)$
1591.00 ± 0.30	Sc^{50} $4\to1$	$\mathrm{Ca}^{50}(\beta^-)$
2013.13 ± 0.30	Ca^{47} $1\to0$	$\mathrm{K}^{47}(\beta^-)$

TABLE III. Some excitation energies in Ca^{47}, Sc^{50}, and Ti^{50}.

Level number	Excitation energy (keV)
Ca^{47}	
1	2013.2 ± 0.3
2	2578.0 ± 0.4
3	2599.0 ± 0.4
Sc^{50}	
1	256.94 ± 0.10
2	328.5 ± 0.2
4 [a]	1848.0 ± 0.3
Ti^{50}	
1	1553.7 ± 0.2
2	2674.8 ± 0.2
3	3198.3 ± 0.2

[a] Transitions to or from the third excited state of Sc^{50} at 761 keV were not observed.

The principal features of the decay of Ca^{50} are illustrated in Fig. 2. The 72-keV Sc^{50} second-to-first excited state and 257-keV Sc^{50} first-to-zeroth excited-state transitions were studied first. Four high-dispersion (0.145 keV/channel) 4096-channel spectra were recorded as explained above with sources of ThC'', Co^{57}, and Hg^{203} positioned to give energy calibration lines of reasonable intensity for use in the energy measurement of the 257-keV line. From these spectra, the 257-keV γ ray was determined to have an energy of 256.94 ± 0.10 keV and to decay with a half-life of 13.7 ± 0.6 sec. The energy of the 72-keV γ ray was measured relative to the accurately known energies of x rays from Pb^{208} and Bi^{208} emitted by the ThC'' source. The portion of the spectra including the 72-keV line and the x rays is illustrated in Fig. 3 which shows the middle two of the four sequential spectra. The energy and area of the 72-keV line were obtained from a four-peak Gaussian fit to the 72-keV line and the three nearby x-ray peaks. The result was 71.54 ± 0.20 keV and a decay half-life of 15 ± 2 sec. No attempt was made to determine the relative intensities of the 72- and 257-keV lines.

An incidental result of this measurement was the observation of a γ ray of 139.78 ± 0.06 keV and $T_{1/2}=48.6\pm3.5$ sec. This we identify as the decay of the metastable first excited state of Ge^{75}, which is presumably formed by neutron capture on Ge^{74}

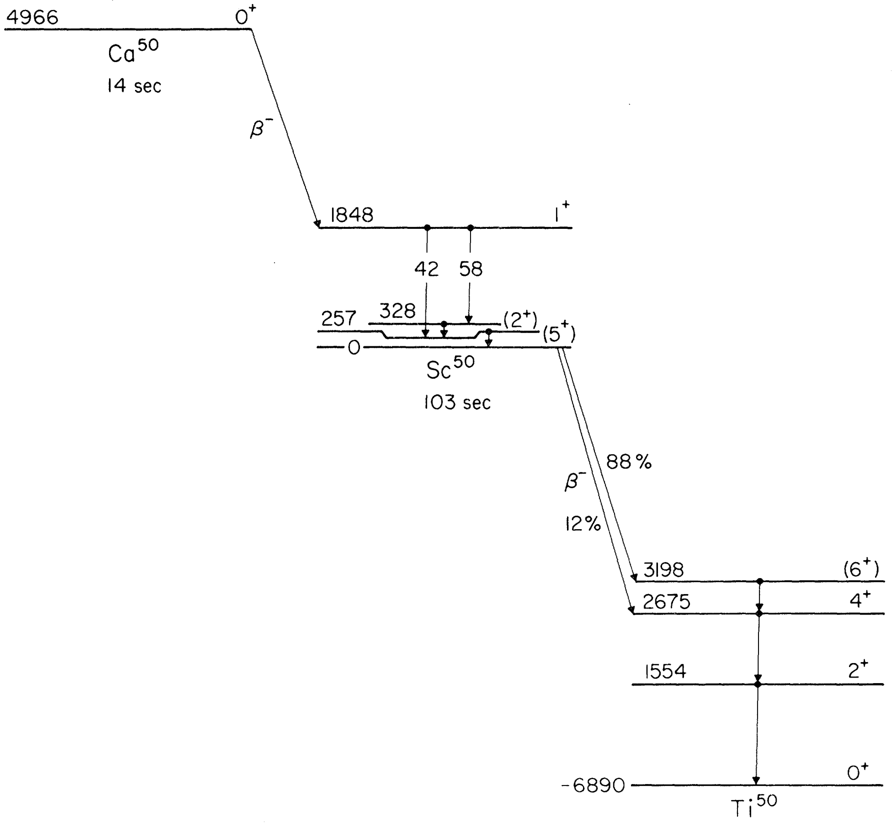

FIG. 2. Decay schemes of Ca^{50} and Sc^{50}. All energies are in keV, the ground-state energies of Ca^{50} and Ti^{50} are relative to Sc^{50}. Uncertain assignments are in parentheses. The third excited state of Sc^{50} at 761 keV has been omitted.

(36.5% abundant) in the Ge(Li) detector.

Decays to or from the 761-keV third excited state[3] were not observed. The energies, half-lives, and relative intensities of the Sc^{50} γ ray lines due to the decay of the 1848-keV fourth excited state to the first and second excited states were determined from spectra recorded in a similar fashion but with lower dispersion. Several different measurements were made. One is illustrated in Fig. 4 which shows the first of the four 18-sec spectra shifted by computer to match the conditions of Fig. 1. This spectrum was collected in ~12 h with the principal aim of determining the relative intensities of the K^{47} lines. The detector was, at this time, beginning to show the effects of neutron damage as indicated by the low-energy tails on the peaks of Fig. 4. From these measurements, the half-lives of the 1519- and 1591-keV lines were determined to be consistent with each other and with those of the 72- and 257-keV lines. Our final adopted half-life for Ca^{50} is 13.9 ± 0.6 sec.

Our results for the energies of the 1519- and 1591-keV lines are included in Table II. The calibration lines used in the determination of those energies are the Sc^{50}, F^{20}, F^{21}, Na^{24}, and Ca^{49} lines

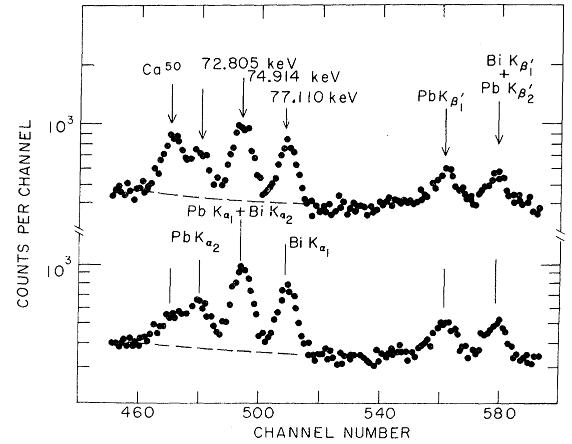

FIG. 3. Portions of the 30-cc γ-ray spectrum used in the determination of the half-life and energy of the 72-keV Sc^{50} 2 → 1 transition following the β^- decay of Ca^{50}. The 72-keV Ca^{50} γ ray is labeled as are various x rays from Pb and Bi. The two spectra shown are the middle two of the four sequential spectra as explained in the text. The energy resolution is 1.1 keV FWHM.

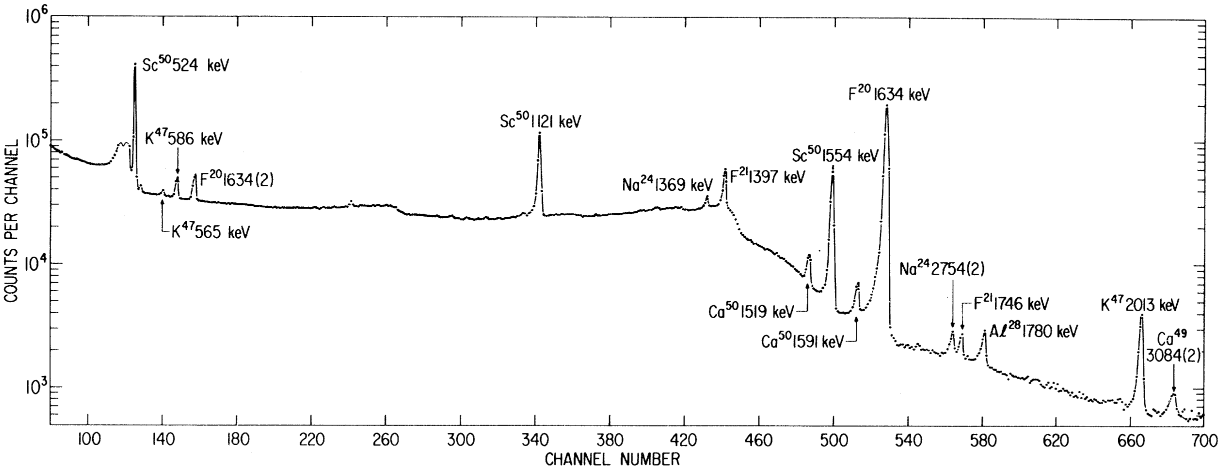

FIG. 4. 30-cc Ge(Li) γ-ray spectrum observed following bombardment of $Ca^{48}F_2$ with a 3.3-MeV triton beam. The original spectrum has been compressed and shifted to match the dispersion and bias of Fig. 1. The spectrum shown is the first of four obtained from the sum of 12 h of 100-sec cycles consisting of a 20-sec irradiation, four 18-sec counting intervals, and an 8-sec wait. γ rays are labeled by the parent activity and by their energies in keV. Two-escape peaks are labeled by energies (in keV) and by the symbol (2). The peak due to 511-keV annihilation radiation is not shown, since it overflowed. The Na^{24} peaks are from $Na^{23}(t,d)Na^{24}$ induced in Na^{23} impurities on the collimator system. The Al^{28} activity is from $Al^{27}(n,\gamma)$ in the detector housing, and the F^{20} and F^{21} activities are from $F^{19}+t$. The other peaks are discussed in the text.

indicated in Fig. 4. For the branching ratios of the Sc^{50} 1848-keV fourth excited state we find (42 ± 2)%, (58 ± 2)%, and <3% for branches to the first, second, and third excited states, respectively. These results are in good agreement with those of CMN[5] which were (37 ± 7)% and (63 ± 13)% for the first two of these branches. No γ rays were observed which were attributable to any other β^- branches from Ca^{50} decay. However, the experiment was not very sensitive to weak branches and so we make no quantitative statements about limits on other branches but, for purposes of discussion, shall assume the decay proceeds 100% to the 1848-keV level.

C. $K^{47}(\beta^-)Ca^{47}$

The most intense γ ray attributable to the decay of K^{47} is that due to the Ca^{47} $1 \rightarrow 0$ transition. This γ ray we find to have an energy of 2013.13 ± 0.30 keV and to decay with a half-life of 18.0 ± 1.0 sec (as compared with the expected values[1,3] of 2016 ± 5 keV and 17.5 ± 0.3 sec, respectively). This is in agreement with Kuroyanagi *et al.*[1] who reported a 2.0-MeV γ ray from K^{47}. However, Kuroyanagi *et al.* reported a 2.6-MeV γ ray with an intensity of 15% relative to 85% for the 2.0-MeV γ ray, while we do not observe a 2.6-MeV γ ray and can set an intensity limit relative to that of the 2013-keV γ ray of <2% for such a radiation. We do observe two γ-ray peaks with energies of 564.74 ± 0.30 and 585.75 ± 0.30 keV and half-lives of 17.2 ± 2.1 and 18.1 ± 1.0 sec, respectively, which we attribute to the decay of the Ca^{47} second and third excited states to the first excited state following $K^{47}(\beta^-)Ca^{47}$. The deduced excitation energies for the Ca^{47} second and third excited states (see Table III and Fig. 5) are in good agreement with the previous values[3] of 2580 ± 5 and 2601 ± 5 keV. We surmise that the 2.6-MeV peak observed by Kuroyanagi *et al.*[1] with a NaI(Tl) detector was possibly due to summing of the Ca^{47} cascade radiations from the second and third excited states through the first excited state.

From the relative Ca^{47} γ-ray intensities deduced from spectra such as Fig. 4, we deduce that the ground-state branches from the 2.58- and 2.60-

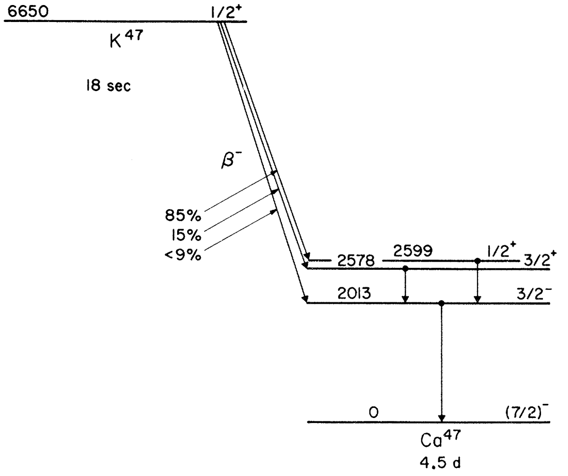

FIG. 5. Decay scheme of K^{47}. All energies are in keV. The spin-parity assignments are our final conclusions based on this and previous work as discussed in the text.

MeV levels are <28% and <2.5%, respectively. The β^- branching ratios given in Table I are obtained assuming 100% cascade via the first excited state for both of these levels.

III. DISCUSSION

Our final results are summarized in Figs. 2 and 5 and in Tables I, II, and III. The results for the decay of Ca^{50} and Sc^{50} are in good agreement with previous work,[5,7] while those for the decay of K^{47} supercede the previous β^- branching-ratio information[1] which is definitely in error.[14]

Our results for $Ca^{50}(\beta^-)Sc^{50}$ add nothing new of theoretical significance. We note that the argument given by CMN[5] in support of a 1^+ assignment to the Sc^{50} 1848-keV level is unnecessarily weak. A stronger case for this assignment comes from the nature of the β^--decay branch to this level. Since the transition to it is allowed and $0^+ \rightarrow 0^+$ transitions with $\Delta T = 1$ are forbidden, it necessarily has $J^\pi = 1^+$. The position of this 1^+ level, the $\log ft$ value for decay to it, and its subsequent γ-ray decay have been the subject of recent theoretical work.[15,16] The theoretical predictions are in rather good agreement with experiment for the excitation energy[15,16] and γ-ray decay modes,[15] but not so good for the β^- decay rate.[15,16]

As indicated in Figs. 1 and 2 the ground state and first three excited states of Ti^{50} appear to form a $0^+, 2^+, 4^+, 6^+$ sequence.[17,18] The spin-parity assignments for the first three are from various direct-reaction studies[18] and appear to be quite firm. The 6^+ assignment for the third excited state is not as definite; however, it would be surprising if it were incorrect.[19] The indicated 5^+ assignment for the Sc^{50} ground state is also not definite. Since the β^- branch of the Sc^{50} ground state to the Ti^{50} 3198-keV third excited state is allowed, these states have the same parity. Also, since the transition to the 4^+ state has $|\Delta J| \leq 1$, the Sc^{50} ground state has $J^\pi = 5^+$ if the 3198-keV level has $J^\pi = 6^+$. Both these latter assignments are predicted theoretically.[15,16] Theoretical predictions for the β^- decay of Sc^{50} to the 4^+ and 6^+ states of Ti^{50} are discussed by Hughes and Soga.[15] Both the observed $\log ft$ values are considerably smaller than the predicted ones, but the ratio of the $\log ft$ values is in good agreement with the predictions.

The $K^{47}(\beta^-)Ca^{47}$ results summarized in Fig. 5 were expected. The fact that both decays are allowed and the K^{47} ground state[4] is $\frac{1}{2}^+$ chooses for the 2578-keV level the $\frac{3}{2}^+$ alternative allowed by the $l = 2$ assignment in the $Ca^{46}(d, p)Ca^{47}$ reaction.[3] If this $\frac{3}{2}^+$ state were a pure $d_{3/2}$-hole state, and the K^{47} ground state and Ca^{47} 2599-keV level were pure $s_{1/2}$-hole states, then the decay to the $\frac{3}{2}^+$ state (2578 keV) would be forbidden and the decay to the $\frac{1}{2}^+$ state (2599 keV) would have a $\log ft$ value roughly the same as that of $H^3(\beta^-)He^3$ ($\log ft = 3.0$) or of the $\frac{1}{2}^+ \rightarrow \frac{1}{2}^+$ decay, $Ne^{19}(\beta^-)F^{19}$ ($\log ft = 3.3$). In actual fact, the $\frac{1}{2}^+ \rightarrow \frac{3}{2}^+$ decay, although relatively weak, is not forbidden and the $\frac{1}{2}^+ \rightarrow \frac{1}{2}^+$ decay is some 30–60 times slower than the presumed $s_{1/2} \rightarrow s_{1/2}$ He^3 and Ne^{19} transitions. Thus, we have definite evidence for the fragmentation of the basic $2s_{1/2}$-hole states constructed by removing a $2s_{1/2}$ nucleon from a Ca^{48} core (and also a Sc^{48} core in the case of Ca^{47}). In particular, there would seem to be considerable $2s_{1/2}$-hole strength at higher excitation energies in Ca^{47} and K^{47}. This conclusion is not inconsistent with the $Ca^{48}(d, t)Ca^{47}$ results of Yntema[20] and the $Ca^{48}(d, He^3)K^{47}$ results of Newman and Hiebert.[4]

There seems to be some difficulty in understanding the properties of the low-lying even-parity states of mass 47.[21] The β^- decay rates given here should provide important data for the testing of any future predictions for these states.

ACKNOWLEDGMENTS

We would like to thank E. der Mateosian for the loan of the $Ca^{48}F_2$ sample.

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†Work performed under the auspices of the U. S. Atomic Energy Commission.

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[14] Also note that if the Ca^{47} ground state has $J^\pi = \frac{7}{2}^-$ as is expected, then the reported branch (Ref. 1) of ≈1% ($\log ft \approx 8.4$) for the decay of K^{47} to this state must certainly be in error, since a $\frac{1}{2}^+ \rightarrow \frac{7}{2}^-$ β^- transition is third forbidden and so must have a $\log ft$ at least several orders of magnitude larger than 8.4 (see Ref. 2).

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PHYSICAL REVIEW C VOLUME 2, NUMBER 4 OCTOBER 1970

Neutron Emission from the Zn^{64} Compound Nucleus Formed in Two Ways: p + Cu^{63} and α + Ni^{60}†

Stuart T. Ahrens, William G. Simon, and Hudson B. Eldridge
Department of Physics, The University of Wyoming, Laramie, Wyoming 82070

(Received 16 March 1970)

The Zn^{64} compound nucleus was formed at an excitation energy of 33.3 MeV using two different target-projectile systems: 26.0-MeV protons on Cu^{63} and 31.3-MeV α particles on Ni^{60}. Neutrons were detected with nuclear emulsions using the internal-radiator method. Exposures were made simultaneously at the following angles: 18, 33, 90, 147, and 162°. The c.m. energy spectra (2–15 MeV) of the two systems are very nearly the same. For both systems symmetry about 90° in the c.m. angular distributions is seen up to about 6 MeV followed by a forward peaking at higher energies. The symmetric (compound-nuclear) parts of the angular distributions differ significantly in anisotropy. For the p + Cu^{63} system the distribution is essentially isotropic while for the α + Ni^{60} system we have an average anisotropy of about 1.4. We also observe for the α + Ni^{60} system a slight but significant increase in anisotropy with energy of the emitted neutron (1.290 ± 0.047 at 2 MeV to 1.649 ± 0.119 at 6 MeV). The changes in average anisotropy, as we change target-projectile systems, are basically consistent with multiple-emission calculations using a rigid-sphere moment of inertia ($r_0 = 1.22$ F). The change in anisotropy with emission energy is not seen in the calculations. It is estimated that, for the p + Cu^{63} and α + Ni^{60} systems, direct-reaction neutrons constitute 5 and 3% of the total observed neutron spectra.

I. INTRODUCTION

In order to isolate and study the role of angular momentum in the statistical decay of a compound nucleus, one often turns to a "Ghoshal-type experiment." Since Ghoshal did his classic work, in which he investigated the decay of the Zn^{64} compound nucleus formed with α particles and protons,[1] many other systems have undergone similar analysis.[2] The typical output of such experiments is usually of the form of either excitation functions or particle spectra.

This work is focused on the Zn^{64} compound nucleus. For this system the low-energy-reaction excitation functions have been well established for several projectile-target combinations,[1-9] but the exact role of angular momentum is still uncertain.[2] Presented here are the results of a study in which the energy spectra (2–15 MeV) and angular distributions (18, 33, 90, 147, 162°) of emitted neutrons were measured and calculated for the reaction systems p + Cu^{63} and α + Ni^{60}, both of which lead to the Zn^{64} compound nucleus at an excitation energy of 33.3 MeV.

In Sec. II we cover the experimental procedures used and present the results. In Sec. III the mea-