Decays of ^{50}Sc, $^{50}Sc^m$, ^{50}Ca, and ^{47}K

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Gamma rays from the decays of ^{50}Sc, $^{50}Sc^m$, ^{50}Ca, and ^{47}K, produced by $^{48}Ca+t$ reactions at $E_t=3.2$ MeV, were investigated with a Ge(Li) detector. A 3.5-MV Van de Graaff and a "rabbit" target-transfer system were used. Precision energy measurements resulted in the following γ-ray energies (in keV): ^{50}Sc, 523.792(18), 1121.124(5), and 1553.768(8); ^{50}Ca, 71.552(5), 256.894(10), 1519.300(20), and 1590.850(30). Relative γ-ray intensities were also measured and more accurate β^- and γ-ray branches in the decay schemes of ^{50}Sc, ^{50}Ca, and ^{47}K were obtained. Limits were set on unobserved branches and, in ^{50}Sc decay, five new β^- branches were found. By using a short timing cycle it was found that a possible β^- branch from $^{50}Sc^m$ to the 2^+ 1554-keV state of ^{50}Ti is $<2.5\%$. An incidental result was a value of 520.436(15) keV for the lowest energy γ ray in ^{83}Rb decay. The β^- decay of ^{50}Sc is compared to shell-model predictions.

I. INTRODUCTION

The initial motivation for the present investigation was to establish a more accurate energy value for the 1554-keV γ ray from the first excited state of ^{50}Ti in connection with studies[1] of the electron-capture decay of ^{50}V to ^{50}Ti. A strong source of these γ rays can be produced from the β^- decay of 1.7-min ^{50}Sc, as in a previous investigation,[2] when an energy value 1553.7(2) keV was obtained. In that work the decay schemes of ^{50}Sc, ^{50}Ca, and ^{47}K, all produced in $^{48}Ca+t$ reactions, were studied. These decays have Q values and half-lives as follows: ^{50}Ca, 4967(8) keV, 13.9(6) sec; ^{50}Sc, 6889(16) keV, 102.6(6) sec; and ^{47}K, 6645(9) keV, 17.5(3) sec.[3–5] During the intervening years the techniques of γ-ray energy and intensity measurements have been improved substantially. Thus, because of the great value of β^--decay information to nuclear spectroscopy the investigation was expanded to a comprehensive study of these three decay schemes. In addition to more accurate energies and intensities for the known decay γ rays, a search was made for previously unobserved decay modes.

The isomer $^{50}Sc^m$, which is at an excitation energy of 257 keV and decays with $T_{1/2}=0.35(5)$ sec by γ-ray emission to the ground state of ^{50}Sc,[3–6] is produced directly in the $^{48}Ca(t,n)$ reaction as well as by ^{50}Ca β^- decay. This state has been tentatively assigned[6] a spin parity $J^\pi=2^+$, and as such it would decay by an $M3$ γ-ray transition to the 5^+ ground state. β^- decay branches can also take place from $^{50}Sc^m$ to states of ^{50}Ti below the Q value of 7146 keV. An upper limit of 10% was placed on the allowed branch to the $J^\pi=2^+$ 1554-keV level by Karras and Kantele.[6] We have made another attempt to observe this branch.

II. METHODS AND RESULTS

A technical improvement at the 3.5-MV Van de Graaff over the previous work[2] was the installation of a "rabbit" target-transfer system operated automatically by a timer programmer. A small sample of $^{48}CaCO_3$ was attached to a rabbit and bombarded with 3.2-MeV tritons. For the studies of ^{50}Sc, ^{50}Ca, and ^{47}K bombardment times were generally 15—30 sec at beam currents of 60—120 nA followed by a short interval and then a counting interval of 20—60 sec after transfer of the rabbit into the control room. As described below, a shorter timing cycle was used to investigate the decay of $^{50}Sc^m$. A Ge(Li) detector was placed 5—14 cm from the transfer line such that the stopping point of the rabbit was on the detector axis. An intrinsic coaxial detector was used for $E_\gamma \gtrsim 250$ keV and a small planar detector for $E_\gamma \lesssim 250$ keV. The efficiencies of the detectors versus E_γ were established with combinations of ^{56}Co, ^{152}Eu, ^{133}Ba, and ^{182}Ta sources[7] following standard procedures. A major source of difficulty in all these measurements was the strong buildup of the 511-keV annihilation γ ray due to the $^{16}O(t,n)^{18}F$ reaction forming ^{18}F of 110-min half-life. It was possible to run for only 20—30 min on each of several available $^{48}CaCO_3$ targets and it was then necessary to wait for several hours for the ^{18}F activity to decay before using the target again.

A. Precision energy measurements

For these measurements the reference source was placed on the detector axis as close as possible to the rabbit. In the case of the ^{50}Sc 1554-keV γ ray, $^{110}Ag^m$ ($T_{1/2}=252$ d) was chosen as a reference since it emits a close-lying γ ray of 1562.302(5) keV.[8] A small sample of silver was irradiated in the Brookhaven National Laboratory (BNL) High Flux Beam Reactor to make the $^{110}Ag^m$. The 1562-keV γ ray is one of the weaker lines in the $^{110}Ag^m$ spectrum and it was necessary to discriminate against the strong low-energy γ rays by placing a 1-cm thick Pb absorber next to the rabbit line between the $^{110}Ag^m$ source and Ge(Li) detector. High dispersion was achieved by operating the 4096-channel pulse-height analyzer at its maximum conversion gain and using a different offset and gain for each run with the offset ranging from 4096 to 5120 channels. Figure 1 shows one of the spectra obtained. Not included in Fig. 1 are some of the other $^{110}Ag^m$ lines used for fixing the energy scale, as well as the 1519- and 1590-keV peaks in the decay of ^{50}Ca whose energies were also determined in the series of measurements on the ^{50}Sc 1554-keV line. In this and all of the other analyses the usual computer fitting procedures were used.[9]

For the 1121.1-keV γ ray of ^{50}Sc the 1115.546(4) keV (Ref. 8) line of ^{65}Zn ($T_{1/2}=244$ d) was used as the principal reference, this source also being made in the reactor by neutron irradiation of a small piece of zinc metal. In order to establish the energy scale a ^{60}Co source, emitting γ rays[8] of 1173.238(4) and 1332.502(5) keV was added. Figure 2 shows one of the runs in the vicinity of the ^{50}Sc-^{65}Zn lines.

From a consideration of various calibration sources that could be used to measure the energy of the 523.5-keV γ ray of ^{50}Sc it was concluded that ^{83}Rb ($T_{1/2}=86$ d) offered the best possibility as a principal calibrator, even though its γ-ray energies are not known with the accuracy that could be obtained with current techniques. The ^{83}Rb γ rays have energies[7] of 520.423(25), 529.653(11), and 552.664(21) keV. A source of ^{83}Rb was made in the BNL 60-inch cyclotron by bombarding a target of NH_4Br with 42-MeV α particles, the ^{83}Br being formed in the $^{81}Br(\alpha,2n)^{83}Rb$ reaction. The powder sample was wrapped in 0.0025-cm thick Al foil and the α particles were degraded in energy by inserting an 80-mg/cm^2 thick Al sheet in front of the sample. Figure 3 shows one of the spectra obtained. Note the high-energy edge of the strong 511-keV line (mainly from ^{18}F decay). To provide more data on the energy scale a ^{207}Bi source was added since this source emits a γ ray of 569.702(2) keV.

The energies of the $^{50}Ca(\beta^-)^{50}Sc$ γ rays of 71.6 and 257 keV were determined relative to the Pb $K\alpha2$ x ray of 72.8042(8) keV and the 264.0755(8) γ ray from ^{182}Ta decay, while ^{133}Ba and ^{152}Eu sources provided secondary standards for the 71.6- and 257-keV γ rays, respectively. A summary of the precision energy measurements is given in Table I. An incidental result included in Table I is an improved value of 520.436(15) keV for the lowest energy γ ray from the ^{83}Rb reference source.

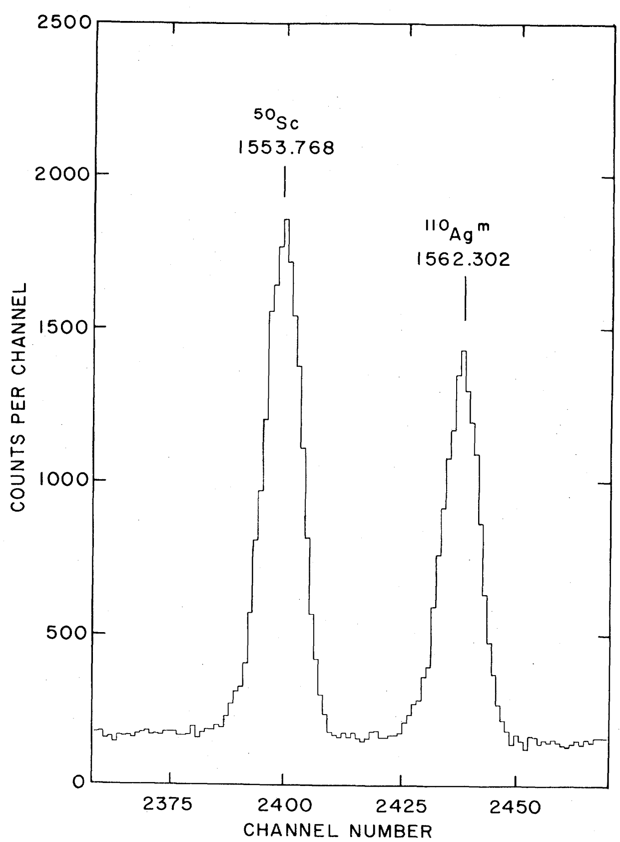

FIG. 1. One of the precision E_γ runs on the ^{50}Sc 1553.768-keV γ ray (presently adopted value) measured relative to the $^{110}Ag^m$ reference line. Other $^{110}Ag^m$ γ rays were also used for calibration. The offset was 4608 channels and the dispersion 0.214 keV/channel.

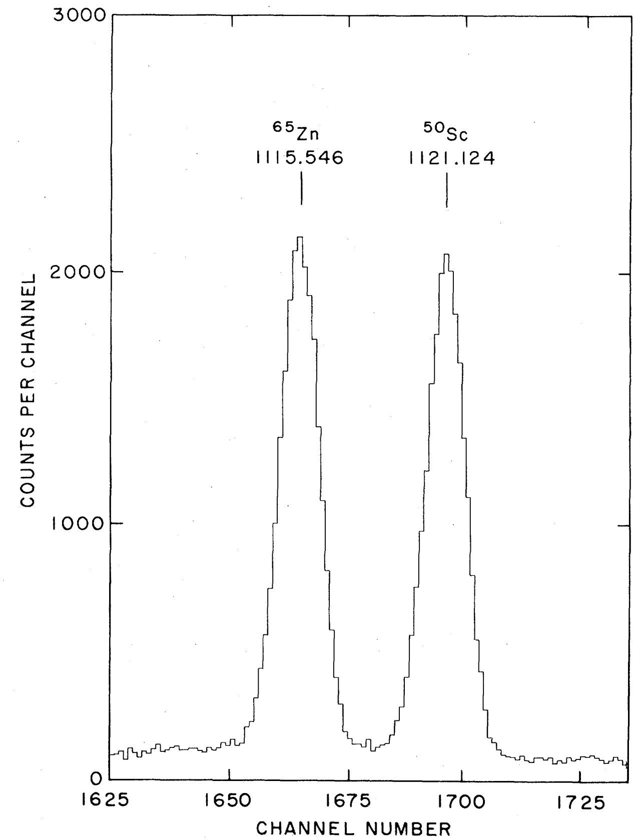

FIG. 2. One of the precision E_γ runs on the ^{50}Sc 1121.124-keV γ ray (presently adopted value) measured relative to the ^{65}Zn reference line. ^{60}Co γ rays were also included for calibration. The offset was 4608 channels and the dispersion 0.179 keV/channel.

TABLE I. Summary of precision energy measurements on γ rays in the decays of ^{50}Sc and ^{50}Ca.

Decaying nucleus	E_γ (keV)[a]	Reference γ ray (keV)[b]	No. of measures	$\lvert E_\gamma - E_{ref} \rvert$ (keV)	Adopted E_γ (keV)
^{50}Sc	523.5(1)	529.653(11) ^{83}Rb	6	5.861(14)	523.792(18)
	1121.0(1)	1115.546(4) ^{65}Zn	9	5.578(3)	1121.124(5)
	1553.7(2)	1562.302(5) ^{110}Ag^{m}	7	8.534(6)	1553.768(8)
^{50}Ca	71.54(20)	72.8042(8) ^{208}Pb x ray[c]	3	1.252(4)	71.552(5)
	256.94(10)	264.0755(8) ^{182}Ta	3	7.182(10)	256.894(10)
	1519.4(3)	1562.302(5) ^{110}Ag^{m}	7	43.002(19)	1519.300(20)
	1591.0(3)	1562.302(5) ^{110}Ag^{m}	7	28.548(30)	1590.850(30)
^{83}Rb	520.423(25)[d]	529.653(11) ^{83}Rb	6	9.212(10)	520.436(15)[e]

[a] Reference 2, except as noted.
[b] References 7 and 8.
[c] J. A. Bearden, Rev. Mod. Phys. 39, 78 (1967).
[d] Reference 8.
[e] Weighted average of the value in the second column and the present result [520.441(15)].

B. Relative γ-ray intensities

Relative γ-ray intensities were extracted from a number of spectra, taken under different conditions in order to enhance the sensitivity to different features of the decay schemes and to mitigate as far as possible the effects of the intense 511-keV radiation from ^{16}O(t,n)^{18}F(β^+)^{18}O. Nine new delayed γ rays were found to arise from ^{48}Ca + t induced reactions. These were so assigned by comparison of spectra from ^{48}CaCO$_3$ and natural CaCO$_3$ targets. An example is shown in Fig. 4. Because of the weakness of these transitions, only cursory time informa-

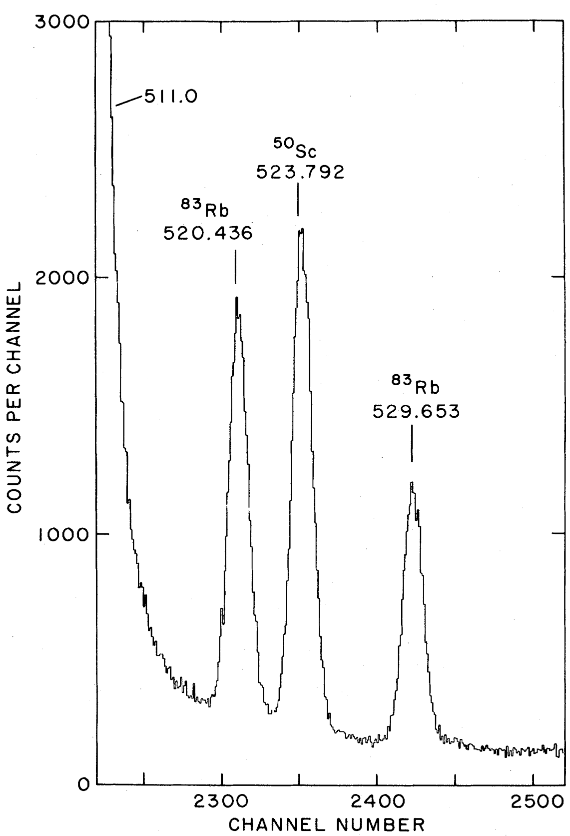

FIG. 3. One of the precision E_γ runs on the ^{50}Sc 523.792-keV ray (presently adopted value) measured relative to ^{83}Rb lines. ^{207}Bi γ rays were also included for calibration. The offset was 4096 channels and the dispersion 0.081 keV/channel.

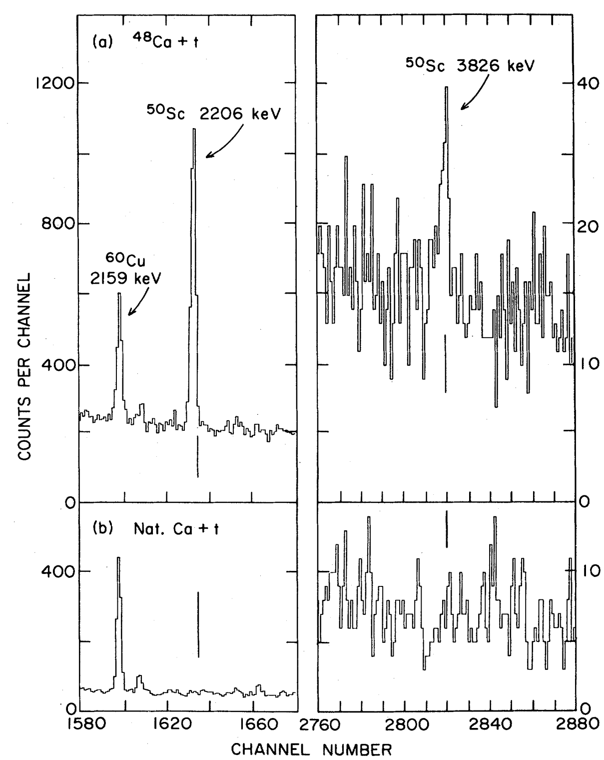

FIG. 4. Portions of γ-ray spectra taken for bombardment of CaCO$_3$ with 3.0-MeV tritons. The ^{60}Cu activity is from the (t,n) reaction induced on a nickel foil used to contain the CaCO$_3$ powder. The top (a) and bottom (b) spectra are for a ^{48}Ca enriched target and a natural target, respectively. The two γ rays are assigned to ^{50}Sc(β^-)^{50}Ti and are the most (2206 keV) and least (3826 keV) intense new decay modes observed in this study.

TABLE II. Relative γ-ray intensities.

Daughter nucleus	E_γ[a]	I_γ (in %) Present	Previous[b]	Transition
^{50}Ti	523.792(18)	88.74(150)	86.3(30)	3199→2675
	1121.124(5)	99.54(90)	98.0(30)	2675→1554
	[1207.8][c]	<0.10[c]		5380→4172[c]
	1472.36(8)	0.61(4)		4147→2675
	[1497.0][c]	<0.10[c]		4172→1554[c]
	1553.768(8)	100.00	100.00	1554→0
	1681.95(7)	0.28(3)		4881→3199
	2205.84(7)	1.27(3)		4881→2675
	2705.15(20)	0.105(16)		5380→2675
	2765.73(20)	0.145(18)		5441→2675
	[2618.1][c]	<0.30[c]		4172→1554[c]
	3132.21(20)	0.251(15)		5807→2675
	3825.99(20)	0.044(10)		5380→1554
^{47}Ca	564.79(8)	14.22(26)	14.0(16)	2578→2013
	586.01(8)	85.39(150)	82.1(3.6)	2599→2013
	2013.45(18)	100.00	100.00	2013→0
	2578.26(12)	6.00(10)	<6	2578→0
	2599.40(20)	1.12(8)	<2	2599→0
	2511.1(8)[d]	1.3(2)[d]		4525→2013[d]
^{50}Ca	71.552(5)	54(5)[e,f]		328→257
	256.894(10)	102(3)[e]		257→0
	[328.45]	<0.7		328→0
	1519.300(20)	62.1(6)	58(2)	1848→328
	1590.850(30)	37.9(6)	48(2)	1848→257

[a] Not corrected for recoil. The number in parentheses is the uncertainty in the least significant figure. Energies in brackets were calculated from the energy level separation.
[b] From the study reported in Ref. 2 but not explicitly given there.
[c] This branch was reported by Ref. 10.
[d] This assignment is speculative and is not included in the final decay scheme. Another possible placement of this γ ray is ^{50}Sc^m(β^-)^{50}Ti (5186-keV level).
[e] Corrected for internal conversion (Ref. 11) with $\alpha(M3)=0.0366$ and $\alpha(M1)=0.0396$ for the 257- and 72-keV γ rays, respectively.
[f] From the decay scheme $I_\gamma(72\text{ keV})=I_\gamma(1519\text{ keV})$. The discrepancy is 15±5 %. A careful consideration of the intensity measurements, repeated three times, did not reveal any reason for the discrepancy which nevertheless is assumed to be experimental but of unknown origin. See the discussion in Sec. II C for elimination of one possible explanation.

tion was obtained from a timing cycle consisting of two 15 sec counting intervals separated by 60 sec delay. From this test it was found that seven of the nine transitions had half-lives greater than 1 min, consistent with the 1.7-min half-life of ^{50}Sc decay, but not with that of either ^{50}Ca or ^{47}K decay. These seven transitions were found to correspond to known or possible γ transitions from five states of ^{50}Ti all with spin-parity assignments of $J^\pi=2^+-5^+$, and thus candidates for allowed β^- decay from $J^\pi=5^+$ ^{50}Sc. The remaining two transitions are assigned to ground-state transitions from the ^{47}Ca 2578- and 2600-keV levels.

The γ-ray relative intensities are presented in Table II. In addition to these results general limitations can be placed on the intensities of γ rays arising from β^- decays to other *known*[4,5] energetically accessible levels of ^{50}Sc, ^{47}Ca, and ^{50}Ti as follows (relative to the units of Table II). ^{50}Sc: any other γ decay to the 257- or 328-keV levels is <0.5%, and any γ decay to the 1847-keV level is <1%, and in particular, γ decay to the 257- or 328-keV levels from any of the possible[5] 1^+ levels of 3682, 3940, and 4640 keV is less than 0.25%; ^{47}Ca: any other γ decay to the first three excited states is <2%; ^{50}Ti: any other γ decay to the first three excited states is <0.2%. β-ray branches derived from the γ-ray intensities are given in Table III together with logft values and the matrix elements derived assuming pure Gamow-Teller decay. Decay schemes for ^{47}K and for ^{50}Ca and ^{50}Sc are shown in Figs. 5 and 6, respectively.

In building β decay schemes from observations on β-delayed γ-ray emission there is usually a problem in how to quantitatively describe any possible unobserved flux. By this we mean any β flux to the ground state and/or to excited states which decay by unobserved γ decays to the ground state or by cascade via any other state not known to be directly fed by the β decay. The custom adopted in

TABLE III. Beta branches, logft values, and deduced Gamow-Teller matrix elements.

Decay	Level populated[a] J_f^π	E_x (keV)	β^- branch[b] (%)	logft	B(GT)[c] ($\times 10^{-3}$)
^{50}Sc(5+)→^{50}Ti	2+	1553.794(8)	<1.5	>7.88	<0.09
	4+	2674.932(10)	8.4(18)	6.67(10)	1.3(3)
	6+	3198.727(20)	88.8(18)	5.388(13)	25.2(5)
	(4)+	4147.31(8)	0.61(4)	6.98(3)	0.63(4)
	(4,5)+	4880.77(6)	1.55(5)	6.00(2)	6.1(2)
	4+	5380.05(15)	0.22(3)	6.34(7)	2.8(4)
	(4,5)+	5440.74(20)	0.145(18)	6.45(6)	2.2(3)
	(4,5)+	5807.25(20)	0.251(16)	5.71(4)	11.9(8)
^{47}K($\frac{1}{2}^+$)→^{47}Ca	$\frac{3}{2}^-$	2013.50(10)	<2.0	>6.68	
	$\frac{3}{2}^+$	2578.31(10)	19.0(3)	5.45(1)	21.7(4)
	$\frac{1}{2}^+$	2599.52(12)	81.0(15)	4.81(1)	95.1(18)
^{50}Ca(0+)→^{50}Sc	(2,3)+	256.895(10)	<5	>6.23	
	(1–3)+	328.447(12)	d		
	1+	1847.772(20)	100.0	4.13(2)	455(20)

[a] The J^π values of the four lowest ^{50}Ti levels and all the ^{47}Ca and ^{50}Sc levels are from Refs. 4 and 5. The other four ^{50}Ti levels are discussed in the text.

[b] For all three decaying bodies the ground-state branch is expected to be negligible and is assumed so. Lower limits (two standard deviations) on N_β, the conversion factor from β^- branch to β^- intensity per 100 decays, are 0.97(^{47}K), 0.92(^{50}Ca), and 0.97(^{50}Sc). See the text.

[c] $B(\mathrm{GT})=6170/ft$.

[d] See footnote f, Table II.

the Nuclear Data Sheets is to assign a normalization factor, N_β, which converts the β^- branch (in %) to β^- intensity per 100 decays. We shall indicate the possible unobserved β flux by setting a lower limit on N_β. For all four β^- decays considered here a ground state branch would be at least second forbidden (e.g., ^{50}Sc^m decay), and

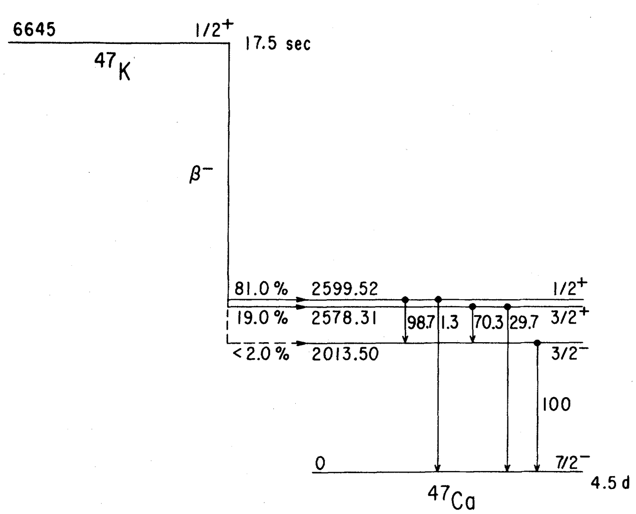

FIG. 5. Decay scheme of ^{47}K.

thus would have an entirely negligible effect on the branching ratios for excited states and thus on N_β. For the decays of ^{47}K, ^{50}Ca, and ^{50}Sc it can reasonably be assumed that any state fed in the β decay will γ decay by a route which eventually feeds the first-excited state. (A small correction is made for ^{47}K decay for which this is not strictly true.) Then it is a simple matter to calculate a limit for N_β from Table II. The results (two standard deviations) are given in Table III.

A fast timing cycle was used to investigate the 0.35-sec 257-keV isomer of ^{50}Sc. This consisted of bombardment of the ^{48}Ca target with a 100-nA beam of 3.2-MeV tritons for 0.5 sec, transfer in 0.4 sec, an immediate 0.4-sec count in one 2048 channel section of a 4096-channel pulse-height analyzer, and a second count of 0.4 sec in the other 2048-channel section. The second count began 2.0 sec after the beginning of the first count, a time sufficient for nearly complete decay of the directly produced isomer. The second time spectrum was similar to those obtained in the relative intensity measurements described above. However, in the first counting interval the 257-keV peak was mostly from direct production via the (t,n) reaction and was more intense than in the second by a factor of 8.5. In the second time bin the 257-keV γ ray arose from the decay of ^{50}Ca to the isomer.

The test for a possible β^- decay branch from the isomer was to see if there was also an excess of counts of the 1554-keV peak in the first time bin as compared with the second. A check was made by showing that the 1121-keV

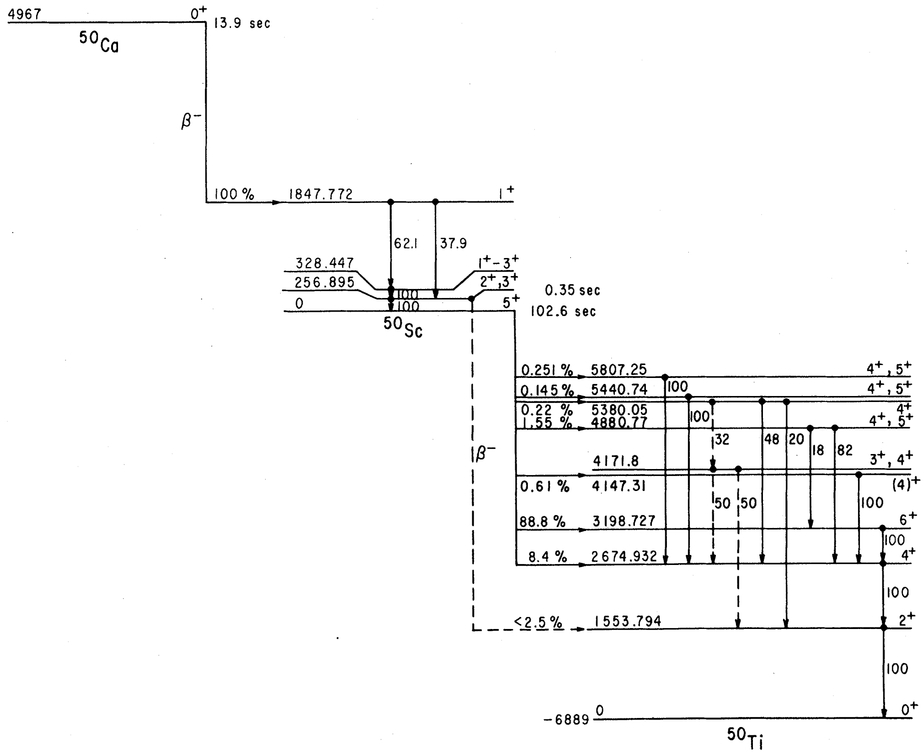

FIG. 6. Decay schemes of ^{50}Ca, ^{50}Sc^m, and ^{50}Sc. The γ decays indicated by dashed arrows were not observed in the present work. They are from Ref. 10.

γ-ray peaks in the two time bins were equal in intensity, after making a 1.4% correction for the ^{50}Sc decay in 2.0 sec. Within the uncertainties, no fast component of the 1554-keV line was observed. From a statistical analysis of the various peaks corrected for γ-ray efficiency it was found that the β^- decay branch from ^{50}Sc^m to the first 2^+ state was $<2.5\%$. The corresponding logft value is >5.2.

An attempt was made to increase the sensitivity in the search for the ^{50}Sc^m β^- branch to the ^{50}Ti 1554-keV level by measuring the 1554-keV γ rays in a Ge(Li) detector (with a short timing cycle) in coincidence with β rays in a plastic scintillator biased so as to exclude lower-energy β rays arising from the ^{50}Sc ground-state decay. Possible β rays from the decay of ^{50}Sc^m to the 1554-keV level would have $E_{\beta\max}=5596$ keV compared with the main ^{50}Sc β-ray branch of $E_{\beta\max}=3695$ keV. Thus, the exclusion of the ^{50}Sc coincidence yield requires a bias that also cuts out all but the highest 1.9 MeV of the ^{50}Sc^m spectrum. Even then the effect of β-γ summing in the plastic scintillator makes it impossible to completely exclude ^{50}Sc. Because of these effects and poor statistics due to low efficiency, the β branching limit obtained from several runs on the sought for ^{50}Sc^m β^- branch was no better than $\lesssim 5\%$.

C. The lifetime of the ^{50}Sc 328-keV level

One possible explanation for the discrepancy between the decay scheme for ^{50}Ca$(\beta^-)^{50}$Sc and the relative intensity found for the ^{50}Sc 328$\rightarrow$257 transition (see Table II) is that this transition contains an appreciable $E2$ component since the internal-conversion coefficient for this 71.6-keV transition is 0.0396 and 1.175 for $M1$ and $E2$, respectively.[11] The single-particle estimates[12] for the mean lifetime of this transition are 8.67×10^{-11} and 3.98×10^{-5} sec for $M1$ and $E2$, respectively. Thus, a straightforward β^--γ timing measurement was performed to probe for a possible $E2$ admixture. A $\gamma\gamma$-TAC (time-to-amplitude conversion) spectrum was measured with an energy gate set on the 71.6-keV γ ray (relative intensity of 72-keV γ rays in gate $=52\%$) and a prompt TAC spectrum was obtained from coincidences between Pb x rays and internal-conversion electrons from ^{207}Bi decay. The prompt resolution function showed a FWHM of 11 nsec. The 71.6-keV γ ray vs β-ray TAC peak had a FWHM of 13 nsec and had a centroid shift corresponding[13] to a lifetime for the 72-keV transition of 5 ± 2 nsec. However, because of possible systematic errors which were not adequately monitored, we choose to quote a lifetime limit, $\tau<10$ nsec, for the ^{50}Sc 328-keV level. This limit corresponds to lower limits on possible 71.6-keV $M1$ and $E2$ transitions of 8.7×10^{-3} and 4×10^{3} W.u. (Weisskopf unit),[12] respectively. The former is reasonable. The recommended[14] upper limit (RUL) for $E2$ strengths in the mass region $A<44$ is 100 W.u. Accepting this RUL for $A=50$ implies at most 2.7% $E2$ contribution to the 71.6-keV transition which further implies limits on the internal conversion coefficient of $0.0396\le\alpha\le0.070$.

Thus it does not appear that an $E2$ contribution to the 72-keV transition can explain the intensity discrepancy (footnote f of Table II). We note that the lifetime limit obtained here also applies to the 1847-keV level which feeds the 328-keV level.

D. Comparison with previous results

1. ^{47}Ca

As summarized in Table II, the present results are in agreement with those previously obtained at this laboratory. The increased sensitivity enabled us to observe the ground-state decays of the 2578- and 2600-keV levels. We obtain branching ratios for the 2578→0 and 2578→2013 transitions of 29.7(5)% and 70.3(5)%. These are in accord with recent results of Mando *et al.*[15] who used the ^{48}Ca(^{3}He,$\alpha\gamma$)^{47}Ca reaction and obtained corresponding branching ratios of 35(5)% and 65(5)%. For the 2600→0 and 2600→2013 transitions our results are 1.3(1)% and 98.7(1)%. The former is an $E3$ transition. Using the lifetime limit,[15] $\tau > 2$ psec, for the 2600-keV level and our branching ratio results in the limit $B(E3) < 108$ W.u. This indicates that the lifetime of the 2600-keV level is considerably longer than the present lower limit.

The predominant part of the ^{47}K wave function can be expressed as ^{48}Ca$(0^{+})\otimes(\pi 2s_{1/2})^{-1}$ and allowed decay to ^{47}Ca is an effective probe for $2s_{1/2}$ hole strength in ^{47}Ca, i.e., proton hole states of the type

$$[(\pi 2s_{1/2})^{-1}(\nu 1f,2p)^{7}(\pi 1f,2p)]$$

coupled to $\frac{1}{2}^{+}$ or $\frac{3}{2}^{+}$ as well as neutron hole states, ^{48}Ca$(0^{+})\otimes(\nu 2s_{1/2})^{-1}$. The latter states can be easily reached by neutron pickup reactions on ^{48}Ca, but the former are hard to reach by other means. The lack of observation of further hole strength below ~5-MeV excitation is in agreement with expectations. However, as the kinematic threshold, i.e., $-Q(\beta^{-})$, is approached the sensitivity for locating the hole strength decreases. For example, assuming a 100% γ branch, the intensity of the possible 4525→2013 transition (see Table II) would correspond to formation of a $J^{\pi}=\frac{1}{2}^{+}$ or $\frac{3}{2}^{+}$ 4525-keV level with $\log ft = 5.38$ and $B(\mathrm{GT})=26(4)\times 10^{-3}$ which is 22% of the summed B(GT) to the 2578- and 2600-keV levels.

2. ^{50}Ca

The present results are in good agreement with the previous investigation at this laboratory and the original investigation of ^{50}Ca(β^{-}) by Chase, McDonald, and Nightingale.[16] A limit of $< 1.2\%$ is placed on the 328→0 branching ratio. Decays to higher-lying ^{50}Sc states were not observed. For orientation, a 0.25% β^{-} branch to the 3682-, 3940-, or 4640-keV levels would correspond to [$\log ft, B(\mathrm{GT})\times 10^{3}$] values of (5.12,47), (4.74,112), and (2.94,7084), respectively. Hughes and Soga[17] have given shell-model predictions for ^{50}Ca decay to the first two 1^{+} states of ^{50}Sc which they predict to be at ~1.8 and 3.8 MeV. These correspond to $B(\mathrm{GT})\times 10^{3}$ values of 214 and 85 with a Soper mixture for the two-body nuclear interaction, while 9 and 427 were obtained with a Rosenfeld mixture. Clearly the Soper mixture gives the better prediction for the first 1^{+} state. Comparison for the second 1^{+} state must await its definite location.

3. ^{50}Ti

To lowest order we expect that $l_{n}=1$ transfer in the ^{49}Ti(d,p)^{50}Ti reaction will proceed via

$$^{49}\mathrm{Ti}[(\pi f_{7/2})^{2}(\nu f_{7/2})^{7}]_{7/2^{-}} \rightarrow {}^{50}\mathrm{Ti}[(\pi f_{7/2})^{2}(\nu f_{7/2})^{7}(\nu 2p_{3/2})]_{J_{f}=2^{+}-5^{+}} ,$$

while Gamow-Teller ^{50}Sc(β^{-})^{50}Ti decay will have a large contribution from

$$^{50}\mathrm{Sc}[(\pi f_{7/2})(\nu f_{7/2})^{8}(\nu 2p_{3/2})]_{5^{+}} \rightarrow {}^{50}\mathrm{Ti}[(\pi f_{7/2})^{2}(\nu f_{7/2})^{7}(\nu 2p_{3/2})]_{J_{f}=4^{+}-6^{+}} .$$

Thus it is not surprising that the five new ^{50}Ti states observed in ^{50}Sc(β^{-})^{50}Ti (Table III) have all been observed with $l_{n}=1$ components in the (d,p) reaction. The lowest-lying three of these levels have recently been observed in a study of ^{50}Ti lifetimes via the ^{49}Ti(d,pγ)^{50}Ti reaction.[10] The decay modes for the 4147- and 4881-keV levels are in fair agreement with present results. For the 5380-keV level, we observe only two of the three decay modes reported by Sona *et al.*[10] As is well known, the thermal neutron capture followed by $E1$ emission bears a strong resemblance to the $l_{n}=1$ (d,p) reaction. Thus, as might be expected, the 4147-, 4881-, and 5380-keV levels are also reported in the ^{49}Ti(n,γ)^{50}Ti reaction.[18] Gamma decay has not been previously reported for the ^{50}Ti 5441- and 5808-keV levels. Since all of the ^{50}Ti levels fed in ^{50}Sc β^{-} decay are known to have even parity and all $\log ft$ values are too small to be second forbidden, we can conclude that all decays are allowed. Thus, the five newly discovered branches are to states with $J^{\pi}=4^{+}$, 5^{+}, or 6^{+} and the limitation $J^{\pi}=2^{+}-5^{+}$ from the (d,p) angular distribution's results in $J^{\pi}=4^{+}$ or 5^{+} for all five levels.

For the 4881-keV level we find branching ratios for decay to the 6^{+} 3199- and 4^{+} 2675-keV levels of 18(2)% and 82(2)% as compared to 12(2)% and 88(2)% from ^{49}Ti(d,pγ)^{50}Ti results.[10] These decay modes are consistent with either 4^{+} or 5^{+} for the 4881-keV level. For the 5380-keV level we observe branches to the 1554- and 2675-keV levels. In addition to these two branches, Sona *et al.* observed a branch of 40% to the lower member of a 4172-keV doublet. For this branch we could only obtain a limit (see Table II) which is consistent with their result. Accepting their relative intensities for the 5380→2675 and 5380→4172 branches, we would obtain branches to the 1554-, 2675-, and 4172-keV levels of 20(4)%, 48(5)%, and 32(5)%, respectively, where a 20% uncertainty was assumed for the relative intensity of the 5380→4172 branch. These branches and the subsequent decay[10] of the 4172-keV level were assumed in calculating the β^{-} decay branches. The decay of the 5380-keV level to the 2^+ 1554-keV level together with the lifetime measurement of Sona *et al.*[10] rules out $J^\pi=5^+$; hence $J^\pi=4^+$ is assigned to the 5380-keV level. In addition, the lifetime establishes the 5380→4172 transition as at least partially dipole so that the 4172-keV level has $J=3$, 4, or 5 from this result, $J=5$ is ruled out by its decay, and even parity is indicated from (d,p) results,[10] hence $J^\pi=3^+$ or 4^+.[19]

E. Shell-model results for ^{50}Ti

Shell-model calculations for the ^{50}Ti energy level spectrum and ^{50}Sc beta decay were performed in an isospin formalism with a model space consisting of

$$[(f_{7/2})^{A-40-n}(p_{3/2},f_{5/2},p_{1/2})^n;n=0,1]\ , \qquad (1)$$

for ^{50}Ti ($A=50$) and the same space but $n=1$ only for ^{50}Sc. Two interactions[20,21] were used both of which were empirically determined by a least squares fit to excitation energies in the $A\sim51-55$ region using the model space given above. These two interactions were determined by Yokoyama and Horie[20] (YH) and van Hees and Glaudemans[21] (vHG). The energy spectra for these two interactions are compared to the experimental spectrum ($E_x\leq5$ MeV) in Fig. 7, while in Fig. 8 a comparison is shown of the observed and calculated Gamow-Teller strength.

From Fig. 7 we note that the two interactions predict the same number of even-parity states below 5-MeV excitation and this number (9) is less than observed (12–15). Thus, this comparison provides evidence that the configurational space considered is too small in the region accessible for ^{50}Sc beta decay. More compelling evidence is provided by the comparison of Fig. 8. The interaction of YH overestimates the Gamow-Teller strength below 6.5-MeV excitation by a factor of 12 and the vHG interaction by 33. Allowing for quenching of up to 50% still leaves a large discrepancy. Part of this discrepancy, also noted by Yokoyama and Horie,[20] is probably due to the difficulty of locating the β^- branches to states near the threshold ($Q=6889$ keV), but the bulk of the discrepancy must be due to deficiencies in the calculations and, in particular, in limitations in the configurational space. For a larger basis, e.g., $n>1$ in Eq. (1), the Gamow-Teller (GT) strength in ^{50}Ti would be expected to be spread over more states so that more strength would be located at energies inaccessible to ^{50}Sc β^- decay. A calculation of the GT strength was made with the vHG interaction and $n=1,2$ for ^{50}Sc in Eq. (1) but still with $n=0,1$ for ^{50}Ti. The resulting summed GT strengths for $J^\pi=4^+$, 5^+, and 6^+ were almost identical to those of Fig. 8. Thus, it would appear that it is the restriction on the ^{50}Ti model space which is most responsible for the inadequacy of the calculation.

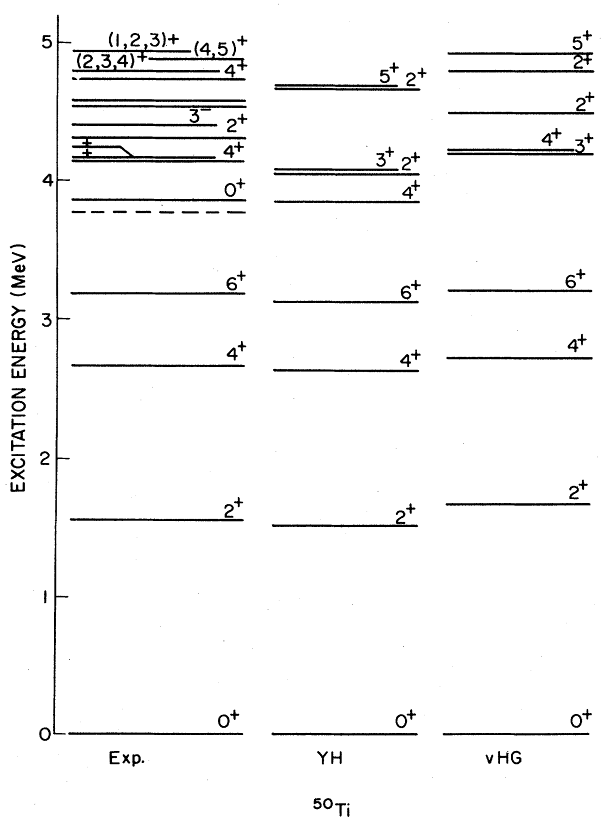

FIG. 7. Energy level spectra for ^{50}Ti. The experimental data are from Ref. 4 and the calculated spectra (see the text) use the interactions of Ref. 20 (YH) and Ref. 21 (vHG).

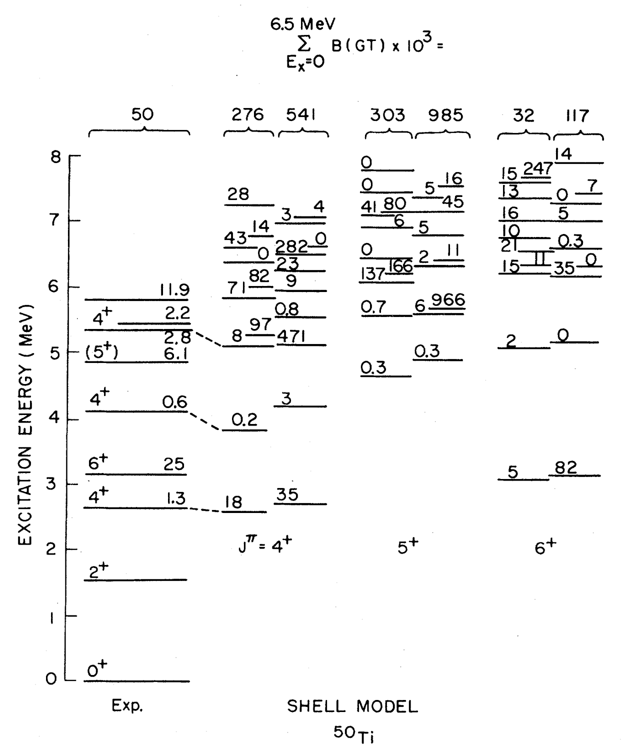

FIG. 8. Comparison of the experimentally observed ^{50}Sc(β^-)^{50}Ti Gamow-Teller (GT) strength to that predicted by shell-model calculations (see the text) using the YH interaction (left-hand side for each J^π column) and vHG interaction (right-hand side for each J^π column). The numbers are the Gamow-Teller transition strengths in units of 10^{-3}, i.e., 10^3B(GT).

The $B(\mathrm{GT})$ for the beta decay of the ^{50}Sc 2_1^+ state to the 2_1^+ state of ^{50}Ti was also calculated with the vHG interaction and the model space of Eq. (1). The result is $10^3B(\mathrm{GT})=49$ as compared to our experimental upper limit of 40.

Note Added. A comprehensive ^{49}Ti(n,γ)^{50}Ti study has just appeared in print [J. F. A. G. Ruyl, J. B. M. DeHaas, P. M. Endt, and L. Zybert, Nucl. Phys. **A419**, 439 (1984)]. This report gives ^{50}Ti γ-ray energy and branching ratio measurements which overlap with the present results. The γ-ray energy measurements are, in general, in good agreement with the present results. There are, however, two rather serious disagreements in γ-branching ratios. These involve the decays of the 4881- and 5380-keV levels. In both cases the weaker of the branches we observe is about twice as intense as observed by Ruyl *et al.* We can find no explanation for this discrepancy. Ruyl *et al.* do not have a 5441-keV level in their ^{50}Ti scheme as we do. However, we note that an unplaced γ ray of 2765.43(12) keV is listed as arising from ^{49}Ti(n,γ)^{50}Ti. The energy of this γ ray is in fair agreement with our value of 2765.73(20) keV for the γ ray from the 5441$\rightarrow$2675 transition. They also list an unplaced transition of 5498.52(16) keV [or E_γ of 5498.20(16) keV] which is in excellent energy agreement with the value of 5498.46(20) keV expected for the capture$\rightarrow$5440.74(20) transition.

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