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Beta decay of ^{51}Sc to states in ^{51}Ti†

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^{51}Sc was produced with the ^{48}Ca(α, p)^{51}Sc reaction at $E_\alpha = 18$ MeV and pneumatically transferred to a shielded counting area. The β decay scheme of ^{51}Sc was determined from measurements of the γ singles and γ-γ coincidence spectra using 50-cm^3 Ge(Li) detectors. This investigation yielded a more accurate determination of the ^{51}Sc half-life (12.4 ± 0.1 s), the observation of previously unknown β branches to ^{51}Ti levels at 2691, 2731, 2919, 3062, 3237, 3619, 4095, 4186, and 4881 keV, and the assignment of new levels in ^{51}Ti at 3062, 4095, and 4186 keV. In addition, the decay scheme provides parity assignments and spin restrictions for a number of states in ^{51}Ti.

[RADIOACTIVITY ^{51}Sc, measured $T_{1/2}, E_\gamma, I_\gamma, \gamma$-$\gamma$ coincidence; deduced decay scheme, logft. ^{51}Ti deduced levels, J, π. Enriched targets, Ge(Li) detectors.]

I. INTRODUCTION

The study of nuclear properties away from β stability aids in the extrapolation of these properties even further from stability. In particular, mass and β-decay systematics are necessary for nucleosynthesis calculations and for estimating Q values of exotic heavy-ion reactions. This study of ^{51}Sc decay is the first in a series of investigations of the β-decay properties of $T_z = \frac{9}{2}$ nuclides in the $1f$-$2p$ shell.

Another motivation for the present work is the further insight into the structure of the daughter nucleus which the β decay can provide. ^{51}Ti, with only three nucleons outside the ^{48}Ca core, is quite amenable to shell-model calculations and provides a convenient example for the study of the interaction of extracore nucleons in different orbitals. The β decay also proceeds to core-excited configurations, yielding information for comparison with possible future calculations.

The nuclide ^{51}Sc was first reported by Bizzeti-Sona, Messlinger, and Morinaga,[1] who produced it via the ^{48}Ca(α,p)^{51}Sc reaction. Using a NaI(Tl) detector, they observed two delayed γ rays with energies of 1.44 and 2.16 MeV and half-lives of about 12 s. In addition, they reported a β group of about 5-MeV end-point energy with a half-life of 12.5 ± 1 s. The γ-ray energies coincided with the energies of two previously known excited states in ^{51}Ti at 1.44 and 2.16 MeV.

Earlier work has provided information on the excitation energies, l values, and spectroscopic factors for low-lying states in ^{51}Ti by means of the ^{50}Ti(d,p)^{51}Ti (Refs. 2–5) and ^{49}Ti(t,p)^{51}Ti (Ref. 4) reactions. γ transitions for low-spin states have been studied with the ^{50}Ti(n,γ)^{51}Ti reaction,[6,7] and for high-spin states via the ^{48}Ca($\alpha,n\gamma$)^{51}Ti reaction.[8] A recent study of the ^{50}Ti($d,p\gamma$)^{51}Ti and ^{48}Ca($\alpha,n\gamma$)^{51}Ti reactions by Lamaze[9] has resulted in a better understanding of the level and decay scheme of ^{51}Ti.

In the present work we have measured the γ singles and γ-γ coincidence spectra following the β decay of ^{51}Sc. The intensity balance of the γ transitions connecting each ^{51}Ti state determines the β branching ratio to that state. In this way nine β branches were inferred in addition to those previously reported,[1] and a more accurate value for the ^{51}Sc half-life was determined.

This study also provides structure information for the daughter nucleus ^{51}Ti. Three of the β branches are to ^{51}Ti states which have not been previously reported. The β-decay scheme and logft values and the subsequent γ-decay scheme provide new spin restrictions and parity assignments to eight levels in ^{51}Ti. Finally, in Sec. V, we will discuss the β-decay scheme in the light of shell-model calculations and other nuclear structure information.

II. EXPERIMENTAL METHOD

The isotope ^{51}Sc was produced in the ^{48}Ca(α,p)-^{51}Sc reaction with an 18-MeV beam from the Argonne National Laboratory FN tandem accelerator. The target consisted of a 1.2-mg/cm^2 rolled foil of 96% enriched ^{48}Ca metal encapsulated between a gold backing 24.5-mg/cm^2 thick and a 100-μg/cm^2 gold window. This assembly was mounted in a Delrin holder of dimensions 0.19 × 2.13 × 2.54 cm. The target was activated *in vacuo* and then transferred to a shielded counting area using a pneumatic target shuttle system ("rabbit"). The control of bombardment, target transfer, and

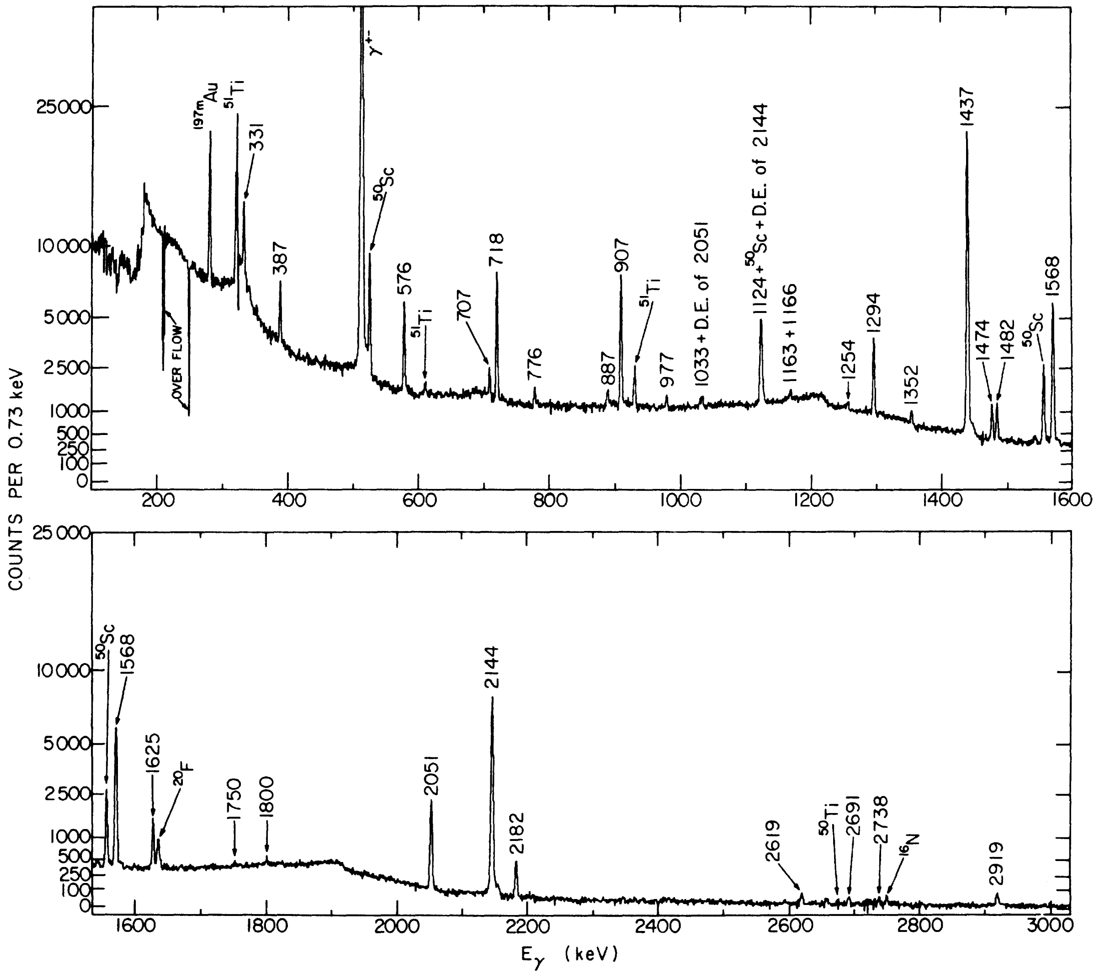

FIG. 1. The delayed γ-singles spectrum. A spectrum measured during a 30-s period has been subtracted from that measured during the previous 30 s. The square root of the number of counts is graphed to reduce the dynamic range. γ rays in ^{51}Ti emitted following the β decay of ^{51}Sc are labeled with their energies in keV. Lines arising from other decays are labeled by the parent nuclei.

computer gating functions was accomplished by means of a crystal-controlled sequence timer.[10]

Delayed γ rays were measured at the counting station using one or two 50-cm^{3}Ge(Li) detectors. To prevent β particles from entering the detectors, polyethylene absorbers of 1.3- and 2.5-cm thickness were positioned between the sample and the detector(s).

For the singles measurement, γ spectra were routed into six 4096-channel time bins, each of 10-s duration. A pulser signal was injected into the Ge(Li) detector preamplifier to facilitate dead-time corrections.

Coincidence data were stored event by event on magnetic tape for subsequent off-line analysis. A coincidence-resolving time of about 30-ns full width was used. In the analysis, the γ spectrum of detector 2 was sorted according to digital gates placed about lines in the spectrum of detector 1. For each window on spectrum 1, a displaced, equal-width window was used to approximately subtract coincidences with the background.

III. RESULTS

A convenient method of enhancing short-lived γ rays is to subtract time bins 4, 5, and 6 from the sum of time bins 1, 2, and 3 after correcting for system dead time. The result of this operation is shown in Fig. 1 to illustrate the singles data. Some examples of the γ-γ coincidence spectra are shown in Fig. 2. A total of 30 γ rays have been attributed to the decay of ^{51}Sc. Of these 27 had sufficient strength to verify that their half-lives were near 12 s. The remaining three lines were observed in coincidence with one or more

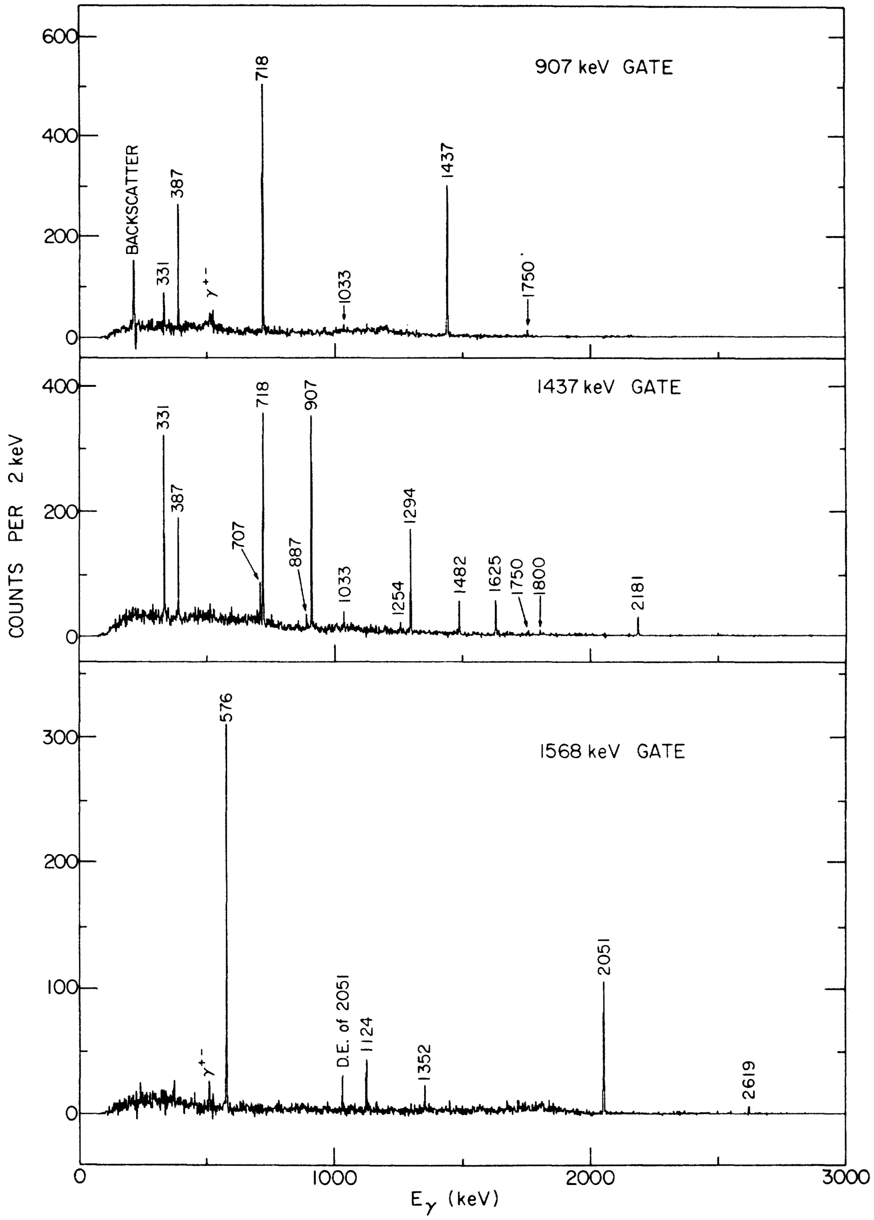

FIG. 2. γ spectra measured in coincidence with the 907-, 1437-, and 1568-keV γ rays. The peak labeled "backscatter" arises from Compton scattering of the intense 1121-keV γ ray from ^{50}Sc decay.

of the other 27. The yields of the 17 strongest γ rays were used to determine the half-life of ^{51}Sc. Their composite decay curve yielded a value of 12.4 ± 0.1 s, in excellent agreement with the earlier measurement.[1]

The energies and intensities of the γ rays attributed to ^{51}Sc decay are listed in Table I as a summary of the experimental data. The relative intensities have been normalized to the strongest transition at 1437 keV and corrected for coincident summing. The full-energy-peak relative efficiency of the Ge(Li) detector as a function of energy was measured using standard sources. In several cases γ-ray intensities could not be determined from the singles measurement. For example, the 1124-keV transition was obscured by the strong 1121-keV γ ray from ^{50}Sc decay as well as by the double-escape peak of the 2144-keV transition. It was seen in coincidence with the 1568-keV γ ray and its intensity was obtained from this spectrum, relative to the other coincident γ rays.

TABLE I. Energies and relative intensities of γ rays in ^{51}Ti observed following the β decay of ^{51}Sc.

E_γ (keV)	I_γ (Relative)	E_γ (keV)	I_γ (Relative)
331.2 ± 0.4	5.49 ± 0.25	1351.8 ± 0.7	1.37 ± 0.13
386.7 ± 0.4	3.52 ± 0.18	1437.3 ± 0.4	100
576.3 ± 0.4	6.44 ± 0.24	1474.4 ± 0.4	3.73 ± 0.20
706.6 ± 0.7	1.82 ± 0.13	1481.9 ± 0.4	4.00 ± 0.20
717.7 ± 0.4	13.72 ± 0.46	1567.5 ± 0.4	28.67 ± 0.91
775.6 ± 0.7	1.17 ± 0.13	1625.0 ± 0.4	6.53 ± 0.27
887.0 ± 0.7	1.61 ± 0.18	1750 ± 2	0.27 ± 0.07
907.2 ± 0.4	17.87 ± 0.59	1800 ± 2	0.57 ± 0.11
977.2 ± 0.7	1.21 ± 0.15	2051.1 ± 0.4	15.87 ± 0.52
1033 ± 2	0.50 ± 0.13	2144.1 ± 0.4	61.16 ± 1.89
1124 ± 1	2.75 ± 0.26	2181.5 ± 0.7	3.73 ± 0.16
1163 ± 1	0.64 ± 0.10	2619 ± 2	0.63 ± 0.08
1166 ± 1	1.23 ± 0.14	2691 ± 2	0.44 ± 0.05
1253.8 ± 1.5	0.76 ± 0.13	2738 ± 2	0.33 ± 0.08
1293.8 ± 0.4	11.77 ± 0.43	2919 ± 2	0.84 ± 0.07

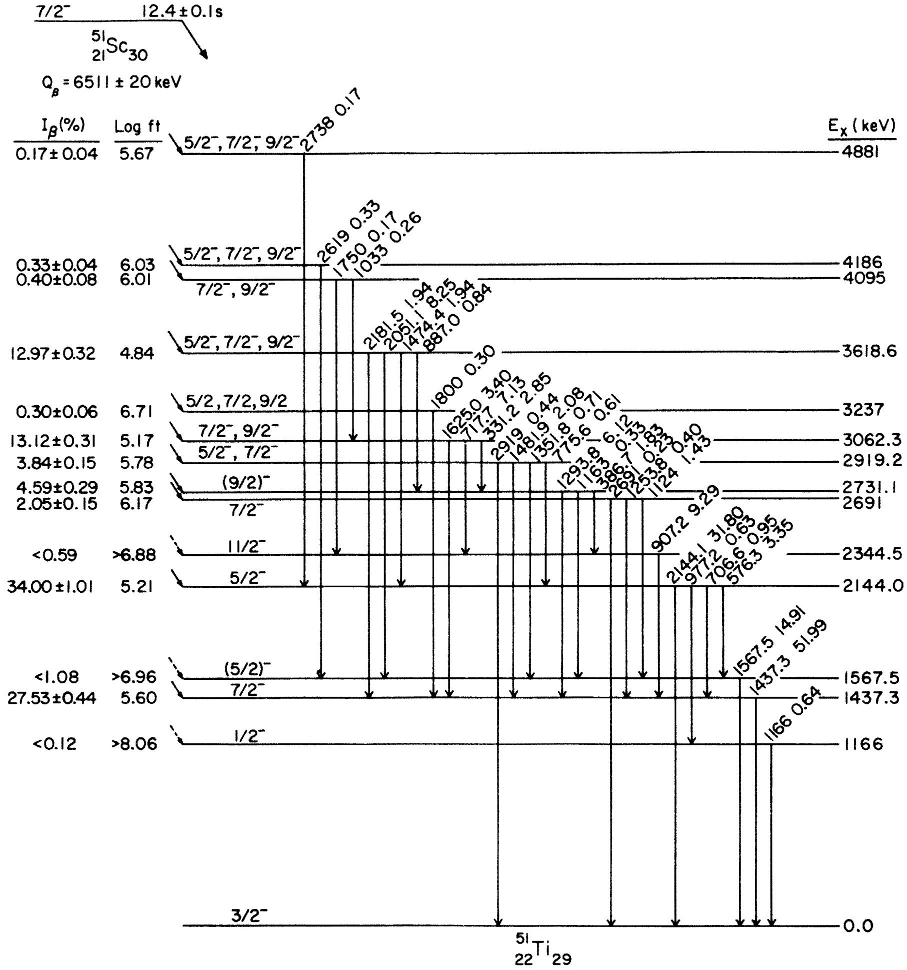

FIG. 3. The decay scheme of ^{51}Sc. Only those ^{51}Ti levels involved in ^{51}Sc decay are shown. Spin and parity assignments are discussed in the text. Assignments for the states below 2700 keV come from previous work, while those for the states above this value result from the present investigation.

Using the results of the γ-ray energies, yields, and coincidence relations, the decay scheme for ^{51}Sc shown in Fig. 3 has been constructed. All 30 γ rays attributed to ^{51}Sc decay have been placed in this scheme. The levels at 2345, 2731, 2919, 3237, and 3619 keV were assigned by Lamaze[9] and confirmed in the present work, while the levels at 3062, 4095, and 4186 keV are newly assigned from the present results. In addition, new transitions at 707, 887, 977, 1163, 1352, 2182, 2691, and 2919 keV were placed in the decay scheme between previously known levels. All other states have been observed previously. The 718-keV transition which was tentatively assigned to a new level at 3473 keV in Ref. 9 has been reassigned in Fig. 3.

The excitation energies which are quoted to 0.1 keV in Fig. 3 are estimated to have an uncertainty of ±0.4 keV, while uncertainties for the other excitation energies are about ±1 keV. These values agree well with the energies quoted in Refs. 8 and 9. The largest difference occurs for the 2919-keV state, which is quoted 2.8 keV higher in Ref. 9.

β branching ratios have been calculated from the γ-ray intensity balance for each ^{51}Ti state. Logft values have been determined from the tables of Gove and Martin,[11] using a total decay energy Q_β of 6511 keV.[12]

IV. β DECAY AND QUANTUM NUMBERS

The shell model predicts $J^\pi = \frac{7}{2}^-$ for the ground state (g.s.) of ^{51}Sc and an $l = 3$ angular distribution was observed in the $^{48}\mathrm{Ca}(\alpha, p)^{51}\mathrm{Sc}$ reaction.[13] Hence, the value $J^\pi = \frac{7}{2}^-$ will be used in the following analysis.

A β-decay branch to the $\frac{3}{2}^-$ g.s. of ^{51}Ti would be a second-forbidden transition with a branching ratio less than 10^{-6}.[14] Therefore, the β branching ratios in Fig. 3 have been calculated by assuming no g.s. branch.

Allowed β decay can proceed only to states in ^{51}Ti with spin-parity values of $\frac{5}{2}^-$, $\frac{7}{2}^-$, or $\frac{9}{2}^-$. Hence, the observation of allowed β decay to the states at 1437, 2144 2731, 2919, 3062, 3619, 4095, 4186, and 4881 keV restricts their spins and parities to these values. The restrictions are consistent with previous spin assignments to the 1437- and 2144-keV levels and provide new information for the other states. Further spin restrictions implied by the γ decay scheme will be discussed below. Within experimental uncertainties the states at 1166, 1568, and 2345 keV are not directly populated by β decay.

The 1568-keV state is populated by $l = 3$ neutron transfer in the $^{50}\mathrm{Ti}(d, p)^{51}\mathrm{Ti}$ reaction,[4] restricting J^π to $\frac{5}{2}^-$ or $\frac{7}{2}^-$. β decay is allowed by the Gamow-Teller selection rules to a state of either spin. Since no β branch is observed, the transition must be hindered for nuclear structure reasons, as discussed in Sec. V. A spin of $\frac{5}{2}^-$ is suggested by shell-model calculations.

The observation of an allowed β branch to the 2731-keV state and its subsequent γ decay to the $\frac{11}{2}^-$ state limit its possible spin and parity to $\frac{7}{2}^-$ or $\frac{9}{2}^-$, since $M3$ γ emission cannot compete with other decay modes of lower multipolarity. The possibility $\frac{7}{2}^-$ is very unlikely because such a low energy $E2$ transition is not expected to compete successfully with more energetic $M1$ decays. For example, if the 1294-keV transition has an $M1$ strength of only 10^{-3} of a single-particle unit, the branching ratio implies an unreasonably large $E2$ strength of 170 single-particle units for the 387-keV transition if $J^\pi = \frac{7}{2}^-$.

A possible spin of $\frac{9}{2}^-$ for the state at 2919 keV is ruled out by the observation of a g.s. decay mode. Similarly, a possible spin of $\frac{5}{2}^-$ is excluded for the levels at 3062 and 4095 keV by the existence of γ transitions to the $\frac{11}{2}^-$ state.

The β-decay rate to the 3237-keV state rules out a first-forbidden unique but not a first-forbidden nonunique transition.[14] Consequently, its parity cannot be determined from the Gamow-Teller selection rules, but its spin is limited to $\frac{5}{2}$, $\frac{7}{2}$, or $\frac{9}{2}$.

V. DISCUSSION

Several shell-model calculations have been made of the ^{51}Ti level scheme using a ^{48}Ca core.[15-17] The model space used by Horie and Ogawa[15] restricts the two additional protons to the $f_{7/2}$ orbital and allows the extra neutron to occupy any vacant f-p orbital. In this calculation the neutron single-particle energies were taken from ^{49}Ca and the proton-proton interactions from the $N = 28$ nuclei. The neutron-proton interactions were obtained by least-squares fitting to selected levels in the $N = 29$ nuclei, including four in ^{51}Ti. The resulting level scheme is compared with the observed one in Fig. 4.

Horie and Ogawa have not calculated β-decay rates. However, the model does help to qualitatively understand the decay scheme. The dominant component in the wave functions of the lowest $\frac{5}{2}^-$ and $\frac{7}{2}^-$ states is predicted to be that in which the two $f_{7/2}$ protons are coupled to $J^\pi = 2^+$ and the extra neutron occupies the $p_{3/2}$ orbital ($J^\pi_p = 2^+ \times p_{3/2}$). This prediction is consistent with the small spectroscopic factor measured in the (d, p) reaction[4] and implies hindered β branches to these states since the Gamow-Teller operator cannot connect the dominant portion of their wave functions with the ^{51}Sc g.s. The difference in the observed β-decay hindrance to the lowest $\frac{5}{2}^-$ and $\frac{7}{2}^-$ states probably depends on small differences in their wave

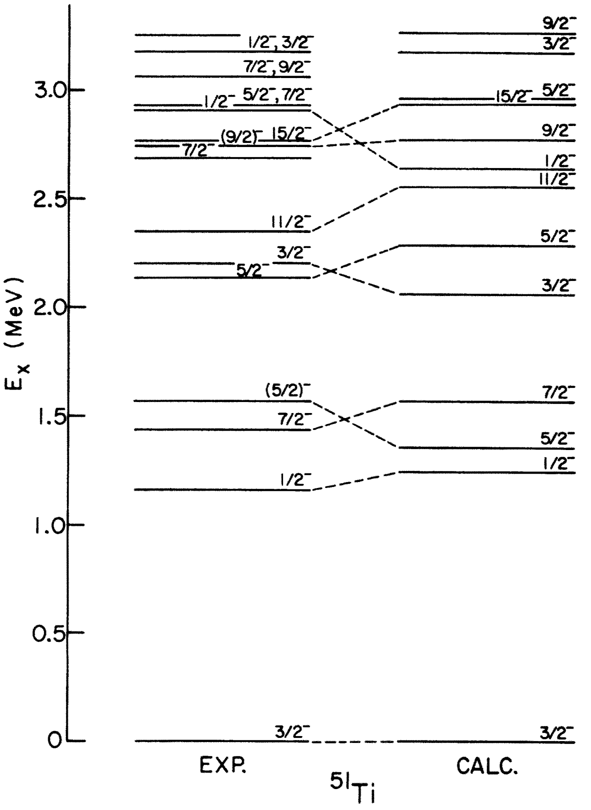

FIG. 4. A comparison of the experimental spectrum of ^{51}Ti with the shell-model calculations of Horie and Ogawa (Ref. 15). Dashed lines indicate probable correspondences.

functions.

The second $\frac{5}{2}^-$ level at 2144 keV is predicted[15] to be predominantly a single-particle state ($J_p^\pi = 0^+ \times f_{5/2}$) and is strongly populated[3,4] in the (d,p) reaction. This state is connected by the β-decay operator with a portion of the ^{51}Sc g.s. wave function in which the neutron pair is elevated to the $f_{5/2}$ orbital. An amplitude of 0.3 for this ^{51}Sc configuration is adequate to account for the observed β rate, using an estimated[18] single-particle $f_{5/2}-f_{7/2}$ logft value of 3.7.

The 2691-keV state is very strongly populated in the ^{49}Ti$(t,p)^{51}$Ti reaction[4] and must have predominantly a two-particle-one-hole (2p-1h) neutron configuration. The absence of a calculated state corresponding to the 2691-keV level is consistent with this interpretation, since a 2p-1h configuration involves core excitation and is not included in the model space of Horie and Ogawa. To the extent that the neutron pair can be regarded as spectators in the β decay to the 2691-keV level, the logft value can be empirically compared with the ^{49}Sc β decay rate to the ^{49}Ti g.s. The logft value of 5.7 in the $A = 49$ case[19] is qualitatively similar, but smaller than the value of 6.2 for the $A = 51$ case.

Strong Gamow-Teller transitions are expected to the configurations involving a $p_{3/2}$ proton and a $p_{3/2}$ neutron coupled to $J^\pi = 1^+$, $T = 0$. In ^{51}Ti this pair then couples to the remaining $f_{7/2}$ proton to produce states of spin $\frac{5}{2}^-$, $\frac{7}{2}^-$, and $\frac{9}{2}^-$. It is likely that the 3062- and 3619-keV levels, which have the lowest logft values, involve such configurations. The β decay of ^{50}Ca to the 1^+, 1848-keV level in ^{50}Sc and of ^{52}Ti to the 1^+, 142-keV level in ^{52}V provide[20,21] empirical values for the expected strength of this transition; log$ft = 4.0$ for both decays. Hence the 3062- and 3619-keV states can account for only 20% of this Gamow-Teller strength in the present system. Presumably the remaining strength lies at higher excitation energies.

In summary, the study of the β-decay scheme of ^{51}Sc provides further information on the structure of ^{51}Ti. The observed β branches are qualitatively consistent with the shell-model calculations of Horie and Ogawa,[15] although some β branches proceed to states not included in their model space. It would be very interesting to see how well a shell-model calculation which includes these structures—a 2p-1h neutron configuration and a 1^+, $T = 0$ p-n pair—can reproduce the observed β-decay scheme.

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