Gamma-ray spectroscopy studies of the lower excited states of ^{53}V†

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Previously unobserved γ-ray decay modes of some excited states of ^{53}V were studied using the $^{51}V(t, p\gamma)^{53}V$ reaction at a bombarding energy of $E_t = 2.9$ MeV. Reaction proton–γ-ray time coincident spectra were obtained using a variety of γ-ray detectors: a 10-cm×10-cm NaI(Tl) detector, a 4-mm×3.81-cm NaI(Tl) detector, a 3.81-cm×5.08-cm NE102 plastic scintillator, and a 20-cm^3 Ge(Li) detector. Lifetime information was deduced from both Doppler-shift attenuations obtained from the Ge(Li) γ-ray spectra, and direct measurements using the plastic scintillator for the γ-ray detector. Some of the measured excitation energies E_x(keV) and lifetimes τ_m are: (127.0±1.4, ≤1 nsec); (227.8±1.6, 5.85±0.44 nsec); (1090.3±2.0, 2 psec ≤τ_m≤ 1 nsec); (1265.4±1.2, 1.6 psec ≤τ_m≤ 1 nsec); (1549.6±3.0, $0.11^{+0.12}_{-0.07}$ psec); (1652.5±3.4, ≥0.65 psec); and (1856.2±2.4, ≤0.04 psec). The experimental results were interpreted with respect to existing nuclear-model calculations and tentative spin assignments were made for a number of excited states.

[NUCLEAR REACTIONS $^{51}V(t,p\gamma)$, E_t = 2.9 MeV; measured E_γ, τ_m, and Γ_γ for transitions in ^{53}V. Deduced tentative J,π assignments for ^{53}V excited states.]

I. INTRODUCTION

Shell-model calculations have now been extended to nuclei which may be described as having many valence particles outside of a closed shell. Such theoretical calculations were carried out for ^{53}V by McGrory[1] and by Horie and Ogawa.[2] In these calculations an inert ^{48}Ca core is assumed and only the nucleons outside of this closed core were considered to be active. The three valence protons were restricted to the $f_{7/2}$ orbits and the two valence neutrons were restricted to the $2p_{3/2}$, $2p_{1/2}$, and $1f_{5/2}$ orbits. Both of these theoretical calculations predict a level sequence which is typical of $(f_{7/2})^{\pm 3}$ nuclei. Since little experimental information concerning ^{53}V existed at the time of these calculations, comparisons of the theoretical results were made only with regard to the general features of the level structure and consequently a full test of the effectiveness of these calculations was never made. In addition, it is interesting to see to what extent this nucleus does approach the extreme of a pure $(f_{7/2})^3$ configuration. The $M1$ transitions are particularly interesting, since they are forbidden between states which are members of a pure $(f_{7/2})^3$ multiplet.

There have been very few experimental studies of the ^{53}V nucleus. The ground state is known[3,4] to have spin and parity $J^\pi = \frac{7}{2}^-$ and most of the presently available information for the excited states has come from the published work of Hinds, Marchant, and Middleton,[4] who used the $^{51}V(t,p)^{53}V$ reaction to measure the differential cross section of the reaction protons with a magnetic spectrometer. Since the ground[3] state of ^{51}V is $J^\pi = \frac{7}{2}^-$, only those states in ^{53}V which can be associated with $L=0$ transfer have been assigned[4] a definite spin and parity, namely that of $J^\pi = \frac{7}{2}^-$. The first six excited states were assigned $\frac{3}{2}^- \leq J^\pi \leq \frac{11}{2}^-$ because the reaction protons populating these states had a characteristic $L = 2$ transfer pattern. The present experiment was initiated in order to gain more experimental information on the radiative decay properties of the excited states of ^{53}V so that a more effective test of the above theoretical calculations could be made.

Part of the present experiment consisted of a study involving proton–γ-ray time coincident measurements using a variety of NaI(Tl) detectors for observing the γ rays. This study resulted in the obtaining of previously unmeasured γ-ray branching ratio data for some of the ^{53}V excited states. In addition, a study was undertaken using a Ge(Li) detector for observing the γ rays; this study centered on obtaining excitation energies, γ-ray branching ratio information, and nuclear lifetime data from the attenuated-Doppler-shift method. The mean nuclear lifetime of the 228 keV state was measured using electronic timing techniques. The experimental details of the above studies are given in Sec. II, while Sec. III presents a synthesis of results. Section IV of this paper contains a general discussion of the ^{53}V excited states.

II. EXPERIMENTAL PROCEDURE

A. NaI(Tl) spectrometer measurements

The $^{51}V(t,p\gamma)^{53}V$ reaction (Q_0 = 7.64 MeV) was used to populate states in ^{53}V at a bombarding energy E_t=2.9 MeV. The triton beam was accelerated by the Lockheed 3.0-MV Van de Graaff generator. The target consisted of a high purity natural vanadium foil rolled to an areal density of 350 μg/cm^2. This part of the experiment was performed in two geometries. In the first of these the protons were detected with a 3000-μm-thick silicon counter positioned at $\theta_{lab} = (70 \pm 3)^0$ with respect to the incoming beam, and in the second the protons were detected in a 1000-μm-thick annular silicon counter positioned about the axis at an angle of $\theta_{lab} = (171 \pm 4)^0$. In the former geometry the proton detector angle was chosen because at this bombarding energy yields to most of the lower excited states were favorable. The proton detectors were shielded from the scattered tritons by an Al foil having an areal density of 10.3 mg/cm^2. During these runs coincident γ-ray spectra are collected using both a 10.16-cm × 10.16-cm NaI(Tl) and a 4-mm × 3.81-cm NaI(Tl) detector positioned at $\theta_\gamma = +45°$ and $-45°$, respectively. The smaller NaI(Tl) crystal was used for the study of γ rays with energies $E_\gamma \leqslant 500$ keV. No attempt was made to collect γ-ray angular correlation data because the high spin ($J = \frac{7}{2}$) of the target nucleus leads to an ambiguous interpretation of the data. Detector signals were processed by conventional modular electronics coupled to analog-to-digital converters (ADC) which were interfaced to an SEL-810A computer used "on line". Further details of this system are given in previously published papers.[5]

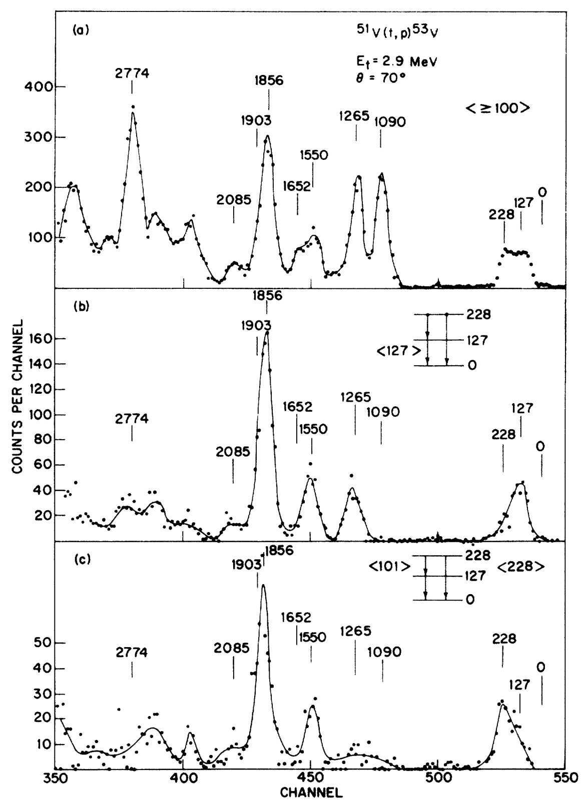

FIG. 1. Proton spectra obtained under a variety of coincidence conditions. Random coincidence events have been removed from these spectra. The peaks are labeled by the excitation energies (keV) of the states to which they belong. The number in the bracket $\langle E_\gamma$ (keV)$\rangle$ represents the γ ray with which the particular spectrum was taken in coincidence. The spectrum was obtained in coincidence (a) with all γ rays $E_\gamma \geq 100$ keV as observed by the 10.16-cm × 10.16-cm NaI(Tl) detector, (b) with the 127-keV γ ray as observed by the 4-mm × 3.81-cm NaI(Tl) detector, and (c) with the 101- and 228-keV γ rays as observed by the 10.16-cm × 10.16-cm NaI(Tl) detector.

Figure 1 illustrates proton spectra obtained under a variety of coincidence conditions. The spectrum at the top of the figure represents the proton pulse-height distribution in coincidence with all γ rays with $E_\gamma \geqslant 100$ keV detected by the 10.16-cm × 10.16-cm NaI(Tl) detector. The proton spectrum of Fig. 1(b) represents these events in coincidence with the photopeak of the 127-keV γ ray detected using the 4-mm × 3.81-cm NaI(Tl) detector. The spectrum of Fig. 1(c) represents those events in coincidence with the photopeaks of the 101- and 228-keV γ rays. The γ-ray branching data shown in Table I were obtained from proton spectra of this nature and from γ-ray spectra obtained in coincidence with various proton groups such as illustrated in Fig. 2.

B. Ge(Li) spectrometer measurements

A 20-cm^3 Ge(Li) detector was used to obtain γ-ray spectra in coincidence with particles stopped in the 1000-μm-thick annular-silicon counter. The γ-ray spectra were measured at $\theta_\gamma = 0°$ and 120°; nuclear level lifetime information was de-

TABLE I. Energies and branching ratios for γ-ray transitions in ^{53}V.

E_i (MeV)	E_f (MeV)	γ ray (keV)	Branch %	Excitation energy[a] (keV)
0.13	0	127.0 ± 1.4	100	127.0 ± 1.4
0.23	0	228.2 ± 2.2	50 ± 5	227.8 ± 1.6
	0.13	100.3 ± 1.8	50 ± 5	
1.09	0	1090.3 ± 2.0	100	1090.3 ± 2.0
1.27	0	1265.7 ± 1.4	63 ± 8	1265.4 ± 1.6
	0.13	1138.3 ± 1.6	28 ± 8	
	1.09	175.0 ± 1.4	9 ± 2	
1.55	0.13	1422.6 ± 2.6		1549.6 ± 3.0
1.65	0	1652.5 ± 3.4	100	1652.5 ± 3.4
1.86	0.13	1729.2 ± 2.0	≥80	1856.2 ± 2.4

[a] Corrected for nuclear recoil.

duced from these spectra using the attenuated-Doppler-shift technique. Also extracted from these spectra were branching-ratio information and excitation energies; these are given in Table I. The branching ratios given in this table are a composite taken from all portions of this experiment. The energy calibration for the Ge(Li) detector was obtained from the ^{18}O (1982.2-keV) and ^{52}Cr (1434.19-keV) lines which appeared in the coincident γ-ray spectra as well as from radioactive calibration sources. The target consisted of a foil of natural vanadium rolled to an areal density of 7.6 mg/cm^2. For further details regarding the procedure for extracting the mean nuclear lifetimes under the above experimental conditions see Ref. 5. The Doppler-shift-attenuation factors and the mean lifetimes derived therefrom are given in Table II as $F(\tau_m)$ and τ_m, respectively.

C. Electronic-timing lifetime measurements

The attenuated Doppler-shift measurements indicated that a number of excited states had lifetimes $\tau_m \geq 0.5$ psec. In addition, nuclear structure arguments suggest that if the 127- or 228-keV state were the $J=\frac{3}{2}$ state with a large percentage of the $(f_{7/2})^3$ configuration it could have a lifetime much greater than a nanosecond. Consequently, an attempt was made to measure nuclear lifetimes by the electronic-timing technique.

The lifetime data was extracted from the time delay distribution between formation and subsequent decay of the states. The formation of the states was marked by the detection, in the 1000 μm annular proton detector, of the reaction proton which corresponds to the population of the state; the decay of the state was determined by the detection of the subsequent deexcitation γ rays in a 3.81-cm$\times$ 3.08-cm NE102 plastic scintillator mounted on an RCA 8575 phototube. The coincident time-delay spectrum was derived from a time-to-amplitude converter (TAC) using "fast" logic signals derived from the above detectors. The coincident data was collected and stored on magnetic tape in such a fashion as to allow a subsequent replay with any desired combination of pulse-height coincident gating conditions. The time delay output of the TAC was calibrated using various lengths of cables of known delay. The estimated uncertainty in the calibration was 2%. The results of this experiment are given in Table II.

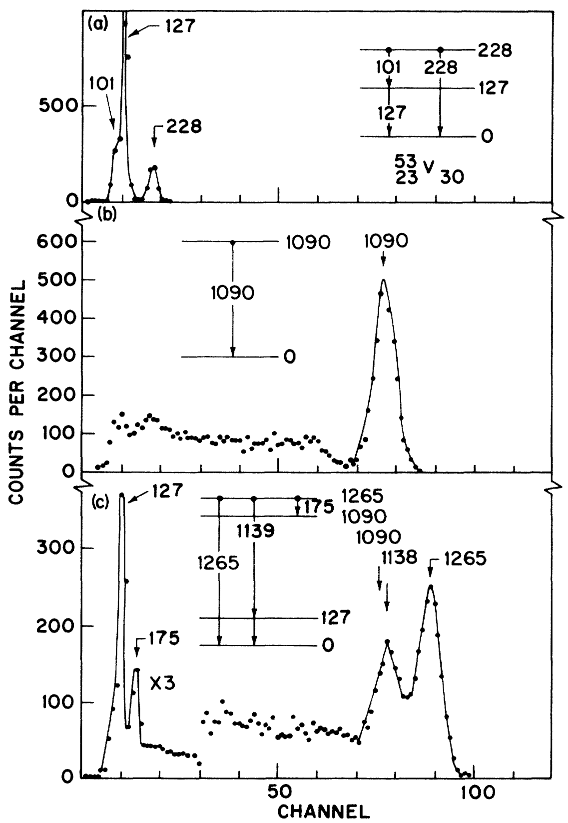

FIG. 2. The γ ray spectrum obtained in coincidence with protons whose energy corresponds to (a) the 127- and 228-keV states, (b) the 1090-keV state, and (c) the 1265-keV state. Random coincidences have been subtracted from all of these spectra. The photopeaks of the γ rays are labeled by their associated energy in keV.

III. SYNTHESIS OF RESULTS

A. 127- and 288-keV states

Although it was not possible to completely separate the proton groups corresponding to these two excited states [see Fig. 1(a)], it was possible to resolve the deexcitation γ rays using the Ge(Li) and the NaI(Tl) detectors. The composite results using these various detectors indicated the excitation energies and branching ratios given in Table I. The calculated full Doppler shifts for the three γ rays originating from these states are too small to measure with the resolution of the Ge(Li) detector system used in this experiment. Figure 2(a) illustrates the γ-ray spectrum observed with the 10.16-cm$\times$10.16-cm NaI(Tl) detector in coincidence with the protons leading to these two states; here the γ rays corresponding to the $288 \rightarrow 0$ and $127 \rightarrow 0$ transitions are clearly separated, while the $228 \rightarrow 127$-keV transition appears as a shoulder on the low energy side of the 127-keV γ ray. Repeated measurements using the various γ-ray detectors lead to the branching ratio for 228-keV state given in Table I.

The data collected during the electronic lifetime measurements for these two states are shown in Fig. 3. A pulse-height-selection requirement on the NE102 scintillator pulses was such that only

TABLE II. The results of lifetime measurements in ^{53}V. The attenuated shift measured between 0° and 120° is represented by ΔE_γ, and $F(\tau_m)$ is the ratio of the attenuated shift to the calculated full shift.

E_x (MeV)	Transition (MeV)	E_γ (keV)	ΔE_γ (keV)	$F(\tau_m)$	τ_m [a] (psec)	τ_m [b] (nsec)
0.13	0.13 → 0	127	···	···	···	≤1
0.23	{0.23 → 0 0.23 → 0.13	228 101}	···	···	···	5.85 ± 0.44
1.09	1.09 → 0	1090	0.31 ± 0.30	0.038 ± 0.037	>2.0 [c]	≤1
1.27	1.27 → 0	1265	−0.46 ± 0.88	−0.048 ± 0.092	>1.6 [c]	≤1
1.55	1.55 → 0.13	1423	6.83 ± 1.96	0.65 ± 0.19	$0.11^{+0.12}_{-0.07}$	···
1.65	1.65 → 0	1652	−1.40 ± 2.45	−0.11 ± 0.20	>0.65 [c]	···
1.86	1.86 → 0.13	1729	11.7 ± 0.7	0.92 ± 0.06	<0.04	≤1

[a] The results of the Doppler-shift attenuation measurements. $K_e = 3.1$ keV cm^2/μg. Errors in τ_m included a ±15% uncertainty in K_e in addition to the experimental uncertainties.
[b] The results of the electronic-timing lifetime measurements.
[c] Lifetime limits correspond to the 90% confidence level.

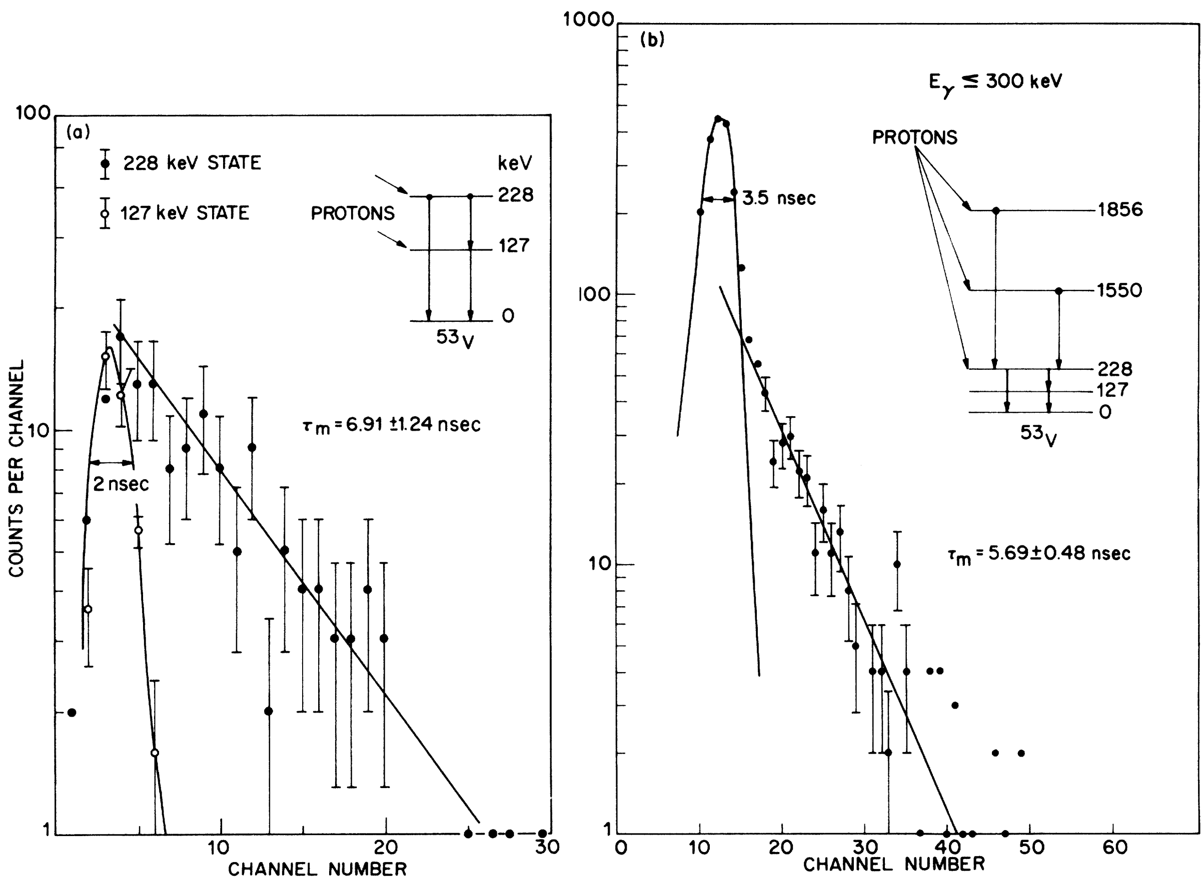

FIG. 3. Experimental decay curves obtained under a variety of conditions. A constant background has been subtracted for each of the delay curves. The mean lifetimes shown in the figure were obtained from a least squares fit to the "delayed" portion of the data after a correction for the influence of the "prompt" portion. The dispersion is 0.8658 nsec/channel. (a) The solid points represent the delay curve obtained for coincident events associated with a proton energy gate set so as to include in the spectrum only those events due to reaction protons populating the 228-keV state in Fig. 1. The open circles represent the "prompt" curve obtained from coincident events associated with an "energy" gate set on the 127-keV state portion of the proton groups. (b) The delay curve obtained for gates simultaneously set on the 1550- and 1856-keV states. The delayed events are due to the lifetime of the 228-keV state. The normalized "prompt" curve was obtained with a gate set on the 1090-keV state.

pulses corresponding to $E_\gamma \leq 300$ keV were accepted. In Fig. 3(a) the solid points represent the time spectrum for events coincident with the protons associated with the population of the 228-keV state; the proton groups populating the 228- and 127-keV states were partially resolved [see Fig. 1(a)]. The open points represent the time spectrum for events coincident with the detection of protons associated with the 127-keV state. The slope of this curve corresponds to a mean lifetime $\tau_m \leq 1$ nsec for the 127-keV state. In Fig. 3(a) the time dispersion is 0.866 nsec/channel. The slope of the delayed curve reflects the lifetime of the 228-keV state, and corresponds to τ_m (228 keV) $=6.91 \pm 1.24$ nsec. The solid line through the data points represents the least-squares fit to the data. Figure 3(b) illustrates the time spectrum taken in coincidence with protons leading to the 1856- and 1550-keV states. These states have lifetimes shorter than that measurable by this method; however, both states decay through the 228-keV state (see Tables I and II), thus the delayed time distribution observed is attributed to the decay of the 228-keV state. The mean lifetime obtained from a least-squares fit to the data (corrected for the influence of the prompt curve) is $\tau_m = 5.59 \pm 0.48$ nsec. The arbitrarily normalized prompt curve was taken from the time spectrum obtained with the proton gate set on the proton group corresponding to the 1090-keV state. The weighted mean and the standard error of the weighted mean for the two measured lifetime values is $\tau_m = 5.85 \pm 0.44$ nsec.

B. States with $E_x \geq 1090$ keV

As can be seen from Fig. 1, the proton groups associated with the formation of the 1090- and 1265-keV states were fully resolved and the p-γ coincident γ ray spectra obtained with the 10.16-cm×10.16-cm NaI(Tl) detectors are illustrated in Fig. 2. The branching ratios for the decay of these two states as well as for the decay of some of the remaining states at higher excitation are given in Table I. This data was deduced from the γ-ray spectra of the NaI(Tl) detector and of the Ge(Li) detector obtained in coincidence with these proton groups. Table II gives the lifetime data for some of the excited states as obtained from the attenuated Doppler-shift measurements. The coincident time spectra observed during the electronic lifetime measurements for the 1090- and 1265-keV states were typically "prompt" and indicated a lifetime $\tau_m \leq 1$ nsec.

IV. DISCUSSION

For ^{53}V, shell-model calculations[1,2] predict a sequence of states, starting with the ground state, of $J^\pi = \frac{7}{2}^-, \frac{5}{2}^-, \frac{3}{2}^-, \frac{11}{2}^-, \frac{9}{2}^-$, and $\frac{1}{2}^-$. Figure 4 illustrates a comparison of the experimental results with the level structure predicted by the Horie and Ogawa[2] calculations. The first six theoretical eigenstates are predominantly due to recoupling members of the $(f_{7/2})^3$ configuration. If a pure $(f_{7/2})^3$ configuration were being dealt with, dipole transitions between these states would be strictly forbidden. The observation of $M1$ transitions attests to the presence of other admixtures, e.g., such as might be expected from the two valence neutrons or such as those resulting from the promotion of one or more protons from the $f_{7/2}$ shell.

Although no spins could be assigned directly from these measurements some conclusions could be drawn on the basis of measured transition probabilities. The first excited state decays 100% to the ground state with a mean nuclear lifetime $\tau_m \leq 1$ nsec. The ground state has $J^\pi = \frac{7}{2}^-$. Consequently, if the 127-keV state had $J^\pi \leq \frac{3}{2}^-$ the mean nuclear lifetime would have to be greater or at least equal to the $E2$ (enhanced by a factor of 10) extreme of 200 nsec. Transition probability arguments limit the spin of the 228-keV state to $\frac{3}{2}^- \leq J^\pi \leq \frac{9}{2}^-$. Based on the above, as well as model predictions and the level structure observed[6,7] in other $(f_{7/2})^{\pm 3}$ nuclei, it is suggested that the 127- and 228-keV states most likely have spin and parity $J^\pi = \frac{5}{2}^-$ and $\frac{3}{2}^-$, respectively. The $E2$ strength of the 228 → 0 keV transition would correspond to an enhancement of 8.4 ± 0.7 W.u. (Weisskopf units). The $E2/M1$ mixing ratios for the 228 → 127 and 127 → 0 keV transitions have not been measured, consequently it is not possible to understand thoroughly to what extent the $M1$ transitions are inhibited. However, from the measured lifetime and branching ratio the 228 → 127-keV $M1$ transition is inhibited by at least 2.3×10^{-3} W.u. over single particle estimates.

Again, based on the present data as well as model predictions and the level structure observed in other $(f_{7/2})^{\pm 3}$ nuclei, the most likely identification of the 1090- and 1265-keV states are with the $J^\pi = \frac{11}{2}^-$ and $\frac{9}{2}^-$ members, respectively, of the anticipated multiplet. The 100% branching of the assumed $J^\pi = \frac{11}{2}^-$, 1090-keV state to the $J^\pi = \frac{7}{2}^-$ ground state and the lifetime limits placed on the 1090-keV state imply an $E2$ strength of $0.04 \leq |M_{E2}|^2 \leq 22$ W.u. The 28% branch of the 1265- to the 127-keV state and the lifetime limits placed on the 1265-keV state imply an $E2$ strength of $0.01 \leq |M_{E2}|^2 \leq 6.2$ W.u.

As for the remaining states, the correspondence to theoretical states is not so clear cut. The remaining $J^\pi = \frac{1}{2}^-$ member of the $(f_{7/2})^3$ multiplet cannot be identified with the 1652- or 1550-keV states since the formation[4] of these states was associated with an $L=2$ transfer. In addition,

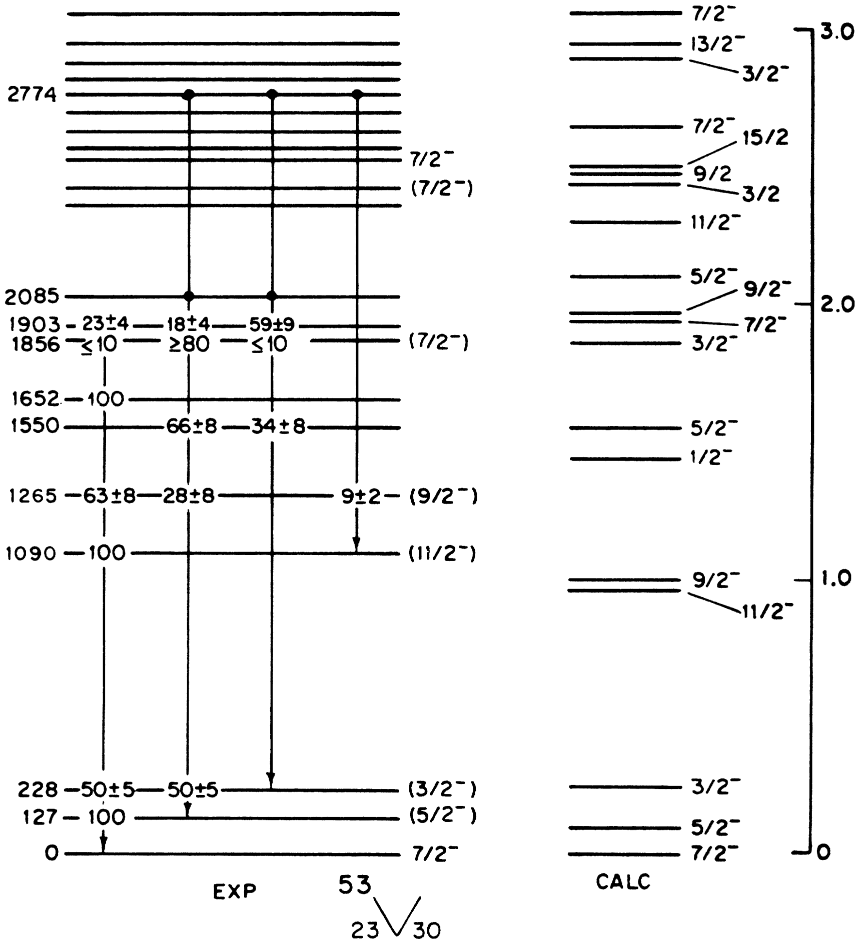

FIG. 4. A comparison of some of the experimental results obtained for ^{53}V with the results of the shell model calculations of Horie and Ogawa (Ref. 2). The spin assignments for the first four excited states are tentative assignments made on the basis of data obtained in the present experiment. The remaining spin assignments are those of Hinds *et al* (Ref. 2)

such an identification would imply an $E2$ strength of $33 \leq |M_{E2}|^2 \leq 192$ W.u. for the 1550→127-keV transition. The 1856-keV state has been tentatively assigned[4] $J^\pi = \frac{7}{2}^-$ on the basis of an $L=0$ component in the (t,p) transfer reaction. The predicted $J^\pi = \frac{3}{2}^-$ and $\frac{5}{2}^-$ states just below 2 MeV excitation are probably predominantly of configurations other than $(f_{7/2})^3$ proton configurations and hence can readily decay by $M1$ transitions. From the data gathered in the present experiment the 1550-keV state could correspond to either one of those predicted states.

A more stringent test of the shell-model calculations would come from an intercomparison of the theoretical and experimental transition matrix elements. In this regard it would be helpful to have additional experimental information such as unambiguous spin assignments and multipole-mixing ratios. This could very likely result from a study using the ^{50}Ti$(\alpha,p)^{53}$V reaction.

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