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Lifetimes of yrast states in ^{51}Ti, ^{52}Ti, and ^{52}V†

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The ^{6}Li and ^{7}Li bombardment of ^{48}Ca in conjunction with recoil distance measurements has been used to measure the mean lifetimes of excited states in ^{51}Ti, ^{52}Ti, and ^{52}V: in ^{51}Ti, 2754-keV level ($\tau = 1.2 \pm 0.4$ nsec) and 2344-keV level ($\tau = 13.9 \pm 2.3$ psec); in ^{52}Ti, 3027-keV level ($\tau = 36.7 \pm 6.3$ psec); in ^{52}V, 2541-keV level ($\tau = 7.7 \pm 0.5$ psec). The γ-ray decay schemes and lifetimes are consistent with an interpretation involving yrast states of the $(\pi 1f_{7/2})^n \otimes (\nu 2p_{3/2}, 1f_{5/2}, 2p_{1/2})^m$ configuration where $n = 2$ or 3 and $m = 1$ or 2. The experimental level energies and $B(E2)$ values are compared with shell model calculations by Horie and Ogawa.

NUCLEAR REACTIONS ^{48}Ca(^{6}Li, $p2n$) $E_{^6\text{Li}}$ = 26 MeV; ^{48}Ca(^{7}Li, $p3n$), ^{48}Ca(^{7}Li, $p2n$), ^{48}Ca(^{7}Li, $3n$) $E_{^7\text{Li}}$ = 28 MeV; measured γ excitations, recoil distance; deduced $T_{1/2}$, $B(E2)$, effective charges, decay scheme in ^{51}Ti, ^{52}Ti, ^{52}V; enriched target, Ge(Li) detectors.

I. INTRODUCTION

Properties of nuclei in the $(1f, 2p)$ shell are presently of considerable theoretical interest. In a previous experiment, a study of nuclei with valence protons of $(\pi 1f_{7/2})^n$ coupled to valence neutrons of $(\nu 2p_{3/2}, 1f_{5/2}, 2p_{1/2})^m$ was carried out via in-beam γ-ray measurements following ^{6,7}Li bombardment of ^{51}V.[1] In the present work, lifetime measurements for high-spin states of this shell-model space in ^{51}Ti, ^{52}Ti, and ^{52}V have been made with the recoil distance method (RDM) following ^{6,7}Li bombardment of ^{48}Ca. The resulting $B(E2)$ strengths and decay schemes provide a good shell-model test for these nuclei. This experiment was carried out in conjunction with a study[2] of the $N=28$ closed-shell ($m=0$) nuclei ^{50}Ti and ^{51}V.

The advantages of heavy-ion induced reactions for RDM lifetime measurements of high-spin yrast states have been utilized for the present ^{6,7}Li + ^{48}Ca experiment.[1] Previous γ-ray studies of these nuclei have aided the interpretation, namely a ^{7}Li + ^{48}Ca study at Munich[3] and a ^{48}Ca($\alpha, n\gamma$)^{51}Ti study by Arnell, Mattsson, and Skeppstedt.[4] Additional information[5-7] on ^{52}V from (d,p), (n,γ), and β-decay studies was also important for the interpretation of the present results. Another study of ^{52}V has recently been made with the ^{50}Ti(^{3}He,p)^{52}V reaction.[8]

A brief summary of the experimental aspects of the RDM related to this work is outlined in Sec. II. The experimental lifetime and $B(E2)$ results are given in Sec. III and summarized in Table I while the relevant energy levels and decay schemes deduced from a synthesis of the present and past work are presented in Fig. 1. Section IV contains a discussion of the results with theoretical comparisons for yrast energy levels and $B(E2)$ values given in Tables II and III, respectively.

II. EXPERIMENTAL TECHNIQUE

The RDM (plunger) apparatus and technique used for the present measurements have been described previously.[9] Metallic targets of ^{48}Ca ~ 150 μg/cm^2 thick were evaporated onto a stretched 5-mg/cm^2 Au foil, and beam energies for the ^{6}Li and ^{7}Li ions of 26 and 28 MeV, respectively, were chosen following excitation measurements. Additional γ-ray excitation measurements were taken for ^{7}Li with a thin ^{48}Ca target on a C backing over the energy range of 22–30 MeV, in steps of 2 MeV. The γ-ray spectra were measured with a Ge(Li) detector at 0° with respect to the beam. For each of the lifetime measurements, the stopped peak (I_0) was clearly resolved from the shifted peak (I_s) for the γ rays used. In Figs. 2 and 3, portions of the γ-ray spectra containing peaks relevant to the present discussion are displayed. The average recoil velocities $\bar{v}$ were extracted from these and other γ-ray peaks in the data. For the ^{6}Li bombardment at 26 MeV, $\bar{v}/c = (0.91 \pm 0.02)\%$ while for

TABLE I. Mean lifetimes and experimental $B(E2)$ values in ^{51}Ti, ^{52}V, and ^{52}Ti.

Nucleus	Transition $E_i \rightarrow E_f$ (keV)	$J_i^\pi \rightarrow J_f^\pi$	$\tau(J_i)$ (psec)	$B(E2)_{exp}$ [a] (e^2fm^4)
^{51}Ti	2754 → 2344	$(\frac{15}{2}^-) \rightarrow (\frac{11}{2}^-)$	1200 ± 400 [b]	58 ± 20
	2344 → 1437	$(\frac{11}{2}^-) \rightarrow \frac{7}{2}^-$	13.9 ± 2.3 [b]	95 ± 16
^{52}V	2541 → 1492	$(9^+) \rightarrow (7^+)$	7.7 ± 0.5 [b]	83 ± 5
^{52}Ti	3027 → 2317	$(6^+) \rightarrow (4^+)$	36.7 ± 6.3 [b]	123 ± 21
	1050 → 0	$2^+ \rightarrow 0^+$	$4.8^{+8.0}_{-2.1}$ [c]	133^{+103}_{-83}

[a] $B(E2) = 813.9/[\tau(\text{psec}) E_\gamma^5(\text{MeV})]$.
[b] Present experiment.
[c] Pronko *et al.*, Ref. 11.

TABLE II. Yrast energy levels for nuclei with $N = 28$ and $N = 29$.

Nucleus	J^π_{exp}	Energy$_{exp}$ (keV)	Nucleus	J^π_{exp}	Energy$_{exp}$ (keV)	Energy$_{th}$ [a] (keV)
^{50}Ti [b,c]	0^+	0	^{51}Ti [d,e]	$\frac{3}{2}^-$	0	0
	2^+	1555		$\frac{7}{2}^-$	1437	1576
	4^+	2676		$(\frac{11}{2}^-)$	2343	2568
	6^+	3200		$(\frac{15}{2}^-)$	2754	2936
^{51}V [b]	$\frac{7}{2}^-$	0	^{52}V [d]	5^+	≡0	≡0
	$\frac{11}{2}^-$	1610		(7^+)	1469	1590
	$\frac{15}{2}^-$	2700		(9^+)	2519	2677
^{52}Cr [b]	0^+	0	^{53}Cr [b]	$\frac{3}{2}^-$	0	0
	2^+	1434		$\frac{7}{2}^-$	1290	1335
	4^+	2370		$\frac{11}{2}^-$	2173	2235
	6^+	3114		$\frac{15}{2}^{(-)}$	3084	3136
	(8^+)	4751		$(\frac{19}{2}^-)$	4696	5310
^{53}Mn [f]	$\frac{7}{2}^-$	0	^{54}Mn	5^+		≡0
	$\frac{11}{2}^-$	1441		7^+		1556
	$\frac{15}{2}^-$	2693		9^+		3108
^{54}Fe [c]	0^+	0	^{55}Fe [b]	$\frac{3}{2}^-$	0	0
	2^+	1408		$\frac{7}{2}^-$	1317	1363
	4^+	2539		$\frac{11}{2}^-$	2540	2391
	6^+	2948		$\frac{15}{2}^{(-)}$	3419	3287

[a] References 14 and 15.
[b] Experimental data from Refs. 1 and 2.
[c] Experimental data from Ref. 16.
[d] Experimental data from the present experiment.
[e] Experimental data from Ref. 4.
[f] Experimental data from Ref. 10.

TABLE III. $B(E2)$ values for yrast transitions in the $N=29$ nuclei.

Nucleus	Transition	$B(E2)_{exp}$ ($e^2\,fm^4$)	$B(E2)_{th}=(Ae_p)^2$ [a] with $\delta e_p=1.2$ ($e^2\,fm^4$)	A (fm^2)	$B(E2)_{th}=(Ae_p+Be_n)^2$ [b] with $\delta e_p=0.9$ $\delta e_n=1.0$ ($e^2\,fm^4$)	A (fm^2)	B (fm^2)
^{51}Ti	$\frac{15}{2}^- \to \frac{11}{2}^-$	58 ± 20 [c]	47	3.12	53	2.92	1.73
	$\frac{11}{2}^- \to \frac{7}{2}^-$	95 ± 16 [c]	103	4.62	92	4.33	1.38
	$\frac{7}{2}^- \to \frac{3}{2}^-$		103	4.62	81	4.23	0.94
^{52}V	$9^+ \to 7^+$	83 ± 5 [c]	85	4.20	82	4.04	1.38
	$7^+ \to 5^+$		116	4.90	104	4.76	1.14
^{53}Cr	$\frac{19}{2}^- \to \frac{15}{2}^-$		101	4.57	90	4.49	0.94
	$\frac{15}{2}^- \to \frac{11}{2}^-$	30^{+16}_{-11} [d]	{130	5.19	124	4.95	1.74
			{86	4.21 [e]			
	$\frac{11}{2}^- \to \frac{7}{2}^-$	{227^{+190}_{-70} [d]	{156	5.68	151	5.50	1.85
		{32 ± 10 [d]	{88	4.27 [e]			
	$\frac{7}{2}^- \to \frac{3}{2}^-$	136 ± 17 [d]	142	5.41	134	5.32	1.45
^{54}Mn	$9^+ \to 7^+$		40	4.26			
	$7^+ \to 5^+$		120	4.97	115	4.94	1.34
^{55}Fe	$\frac{15}{2}^- \to \frac{11}{2}^-$		50	3.20	46	2.94	1.24
	$\frac{11}{2}^- \to \frac{7}{2}^-$	17 ± 6 [d]	108	4.73	99	4.54	1.31
	$\frac{7}{2}^- \to \frac{3}{2}^-$	210 ± 90 [d]	109	4.74	121	4.95	1.59

[a] Theoretical $B(E2)$ values calculated assuming stretched configurations $J_i=J_i'+\frac{3}{2}$ and $J_f=J_f'+\frac{3}{2}$ where J' are the $(f_{7/2})^n$ configurations (Ref. 10) in the neighboring $N=28$ nuclei. $B(E2)[J_i\to J_f]=B(E2)[J_i'\to J_f']$. $\hbar\omega=41A^{-1/3}$ MeV.

[b] Theoretical $B(E2)$ values calculated using microscopic wave functions of the form $[(\pi 1f_{7/2})^n \otimes (\nu 2p_{3/2}, 1f_{5/2}, 2p_{1/2})]$ from Refs. 14 and 15. $\hbar\omega=41A^{-1/3}$ MeV.

[c] Present experiment, see Table I.

[d] Reference 1.

[e] Assuming the seniority mixed $(1f_{7/2})^4\ 4_1^+$ wave function discussed in Ref. 10.

the ^7Li bombardment at 28 MeV, $\bar{v}/c=(1.00\pm0.02)\%$. The ratios $R=I_0/(I_0+I_s)$ as a function of the target to stopper distance D were evaluated from the peak areas I_0 and I_s following subtraction of a fitted background. The experimental values of $R(D)$ for two transitions in ^{51}Ti obtained from the ^6Li bombardment are given in Fig. 2, while the similar quantities for transitions in ^{52}Ti and ^{52}V obtained from the ^7Li bombardment are given in Fig. 3. Portions of the γ-ray energy spectra are also shown for two values of D. The $R(D)$ curves for the ^{51}Ti transitions show the influence of two lifetimes and were analyzed accordingly.[10] For the ^{52}Ti and ^{52}V transitions, only one lifetime was observed and the data were fitted by an iterative nonlinear least squares code to an expression of the form $R=A\exp(-D/\bar{v}\tau)+B$, where A, B, and τ were allowed to vary. The quantity B was included to take account of uncertainties in background subtraction and the occurrence of small distance independent stopped peaks. Small corrections were made to this simple expression above to adjust for the efficiency change of the Ge(Li) detector as a function of energy, solid angle effects, and the small spread in velocity of the recoiling nuclei. Errors of ±1.5 μm were assigned to the uncertainty in the relative distance settings.

III. EXPERIMENTAL RESULTS

A. ^{51}Ti

Arnell, Mattson, and Skeppstedt[4] have established the positions of the lowest yrast levels in ^{51}Ti. Their data are consistent with spin assignments of $\frac{7}{2}^-$, $(\frac{11}{2}^-)$, and $(\frac{15}{2}^-)$ to the levels at 1437, 2344, and 2754 keV as shown in Fig. 1. The three γ-ray transitions in the observed cascade connecting these states are $(\frac{15}{2}^-)\to(\frac{11}{2}^-)$ 410 keV, $(\frac{11}{2}^-)\to\frac{7}{2}^-$ 907 keV, and $\frac{7}{2}^-\to\frac{3}{2}^-$ 1437 keV. In the lifetime measurements of these states, the 410-

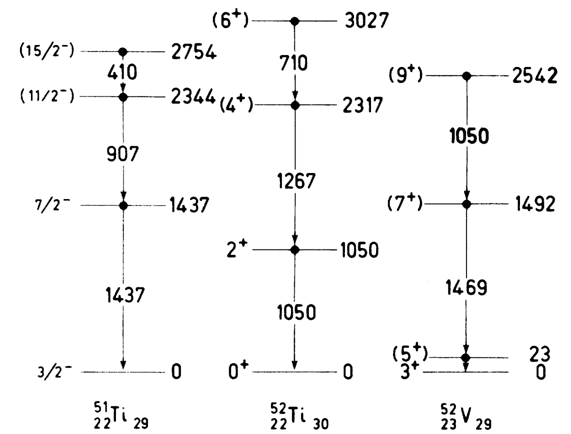

FIG. 1. The relevant energy levels and decay schemes for the three nuclei studied in the present paper. Lifetimes were measured for the ($\frac{15}{2}^-$) 2754-keV and ($\frac{11}{2}^-$) 2344-keV levels in ^{51}Ti, the (6$^+$) 3027-keV level in ^{52}Ti, and the (9$^+$) 2541-keV level in ^{52}V.

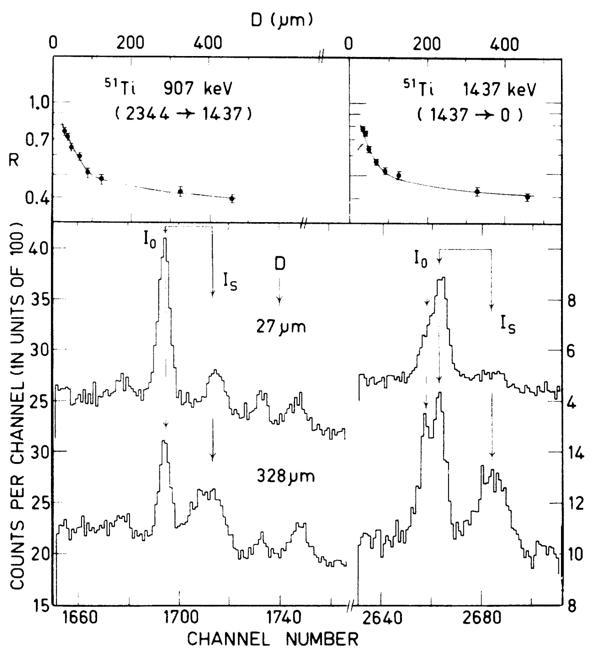

FIG. 2. The lower part of the figure shows representative recoil-distance γ-ray spectra obtained for the 907- and 1437-keV transitions in ^{51}Ti. The target-stopper distances are, as indicated, 27 and 328 μm. The contaminant on the left hand side of the stopped peak (I_0) for the 1437-keV γ ray arises from the ^{52}V β decay to the first excited state of ^{52}Cr at 1434 keV. The upper part of the figure shows the experimentally determined ratio $R(D)$ data; the two curves are the two-lifetime least squares fits to the data. The lifetimes so determined are $\tau = 1200 \pm 400$ psec for the 2754-keV level and $\tau = 13.9 \pm 2.3$ psec for the 2344-keV level in ^{51}Ti. The scales on the right of the figure have the same significance as those on the left.

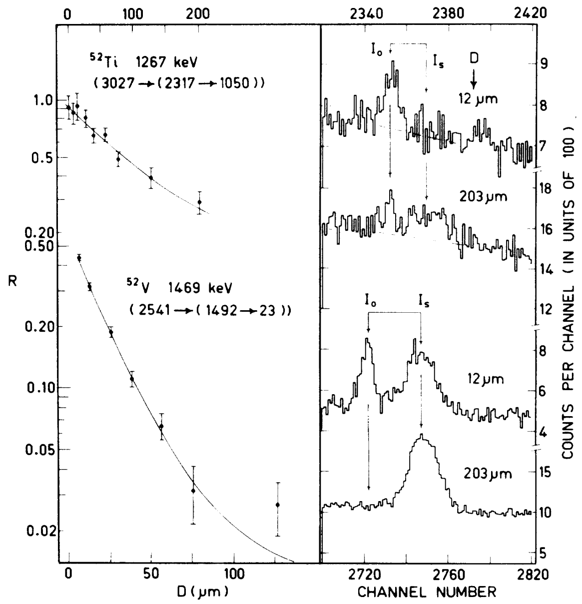

FIG. 3. Representative recoil-distance γ-ray spectra for the 1267-keV transition in ^{52}Ti (at top) and the 1469-keV transition in ^{52}V (at bottom) are shown in the right hand side of the figure for the target-stopper distances of 12 and 203 μm. The experimentally determined ratio $R(D)$ data are shown on the left; the two curves are the least squares fits, assuming one lifetime only, to the data. The lifetimes so determined are $\tau = 36.7 \pm 6.3$ psec for the 3027-keV level in ^{52}Ti and $\tau = 7.7 \pm 0.5$ psec for the 2541-keV level in ^{52}V. The scales on the top of the figure signify, as for the bottom, D(μm) and channel number.

keV γ ray could not be used because of a strong γ ray of 411 keV resulting from the interaction of the ^{6,7}Li beams with the Au target backing and stopper. Both the 907- and 1437-keV γ rays, however, showed evidence of two lifetimes in the ratio data. Analysis of the ratio data obtained with the ^{48}Ca(^{6}Li, $p2n$)^{51}Ti reaction for these two γ rays, which are presented in Fig. 2, and similar data for the 907-keV γ ray obtained with the ^{48}Ca(^{7}Li,$p3n$)^{51}Ti reaction yielded consistent mean lifetimes of $\tau = 1200 \pm 400$ and 13.9 ± 2.3 psec for two-lifetime fits. These fits[10] imply a mean lifetime $\tau = 1200 \pm 400$ psec for the ($\frac{15}{2}^-$) 2754-keV level and $\tau = 13.9 \pm 2.3$ psec for the ($\frac{11}{2}^-$) 2344-keV level in ^{51}Ti. The observed lifetimes for the 2754- and 2344-keV levels, together with the lack of influence in the ratio data of the lifetime of the 1437-keV level, are consistent with the γ-ray energies of these previously implied $E2$ transitions.

B. ^{52}Ti

The position of the lowest 2$^+$ state in ^{52}Ti has been established by ^{50}Ti(t,p)^{52}Ti and ^{50}Ti($t,p\gamma$)^{52}Ti studies.[11] Gögelein[3] has shown that γ rays of 1267 and 710 keV are coincident with the 1050-keV γ ray deexciting the 2^+ level and has identified these γ rays as originating at the (4^+) and (6^+) yrast levels in ^{52}Ti at 2317 and 3027 keV, respectively. Gögelein[3] further showed that the ^{7}Li bombardment of ^{48}Ca at 30 MeV fed the (6^+) state directly.

In the effort to measure the lifetime of the (6^+) state at 3027 keV, the 710-keV γ ray was difficult to use because of the high background from neutron excitation of the 692-keV 0^+ state in ^{72}Ge within the Ge(Li) detector. Also the 1050-keV γ-ray peak did not yield useful lifetime information since it turned out to be a doublet; this will be discussed later. The 1267-keV γ ray, however, showed one lifetime which represents the decay curve of the (6^+) 3027-keV state; the lifetime of the (4^+) 2317-keV state was too short to influence the ratio data. A mean lifetime of $\tau = 36.7 \pm 6.3$ psec for the (6^+) 3027-keV state in ^{52}Ti was extracted from the fit to ratio data shown in the upper part of Fig. 3. These data were obtained from the ^{48}Ca(^{7}Li, $p2n$)^{52}Ti reaction.

C. ^{52}V

On the basis of empirical calculations,[12] the ^{48}Ca(^{7}Li, $3n$)^{52}V reaction is predicted to have a peak cross section at a ^{7}Li energy of 22 MeV while those for the ^{48}Ca(^{7}Li,$p2n$)^{52}Ti and ^{48}Ca(^{7}Li, $4n$)^{51}V reactions are predicted at 28 and 38 MeV, respectively. The cross sections for the (^{7}Li,xn) reactions are also expected to be larger than those for the reactions that include the evaporation of a proton. The excitation measurements of the present experiment with ^{7}Li and those of Gögelein[3] are consistent with the above peak cross-section predictions for the known γ rays from ^{51}V and ^{52}Ti. In addition to these, a strong but unidentified γ ray of 1469 keV exhibited the excitation function expected for the ^{48}Ca(Li, $3n$)^{52}V reaction. Gögelein[3] observed that this 1469-keV γ ray was in coincidence with a window set on the 1050-keV γ-ray peak. Since this window corresponds to the energy of the first excited 2^+ state in ^{52}Ti, he tentatively assigned the 1469-keV γ ray to the deexcitation of a level at 2519 keV in ^{52}Ti.

In the present experiment with the ^{7}Li beam the strong 1469-keV γ ray was observed, in the ratio data, to exhibit a single lifetime. The summed intensities of the 1267- and 1469-keV γ rays (see Fig. 1) in the present data, however, exceeded the intensity of the 1050-keV peak by 8%, and hence both of these γ rays could not be feeding the 1050-keV 2^+ state in ^{52}Ti. This suggests that the 1050-keV γ-ray peak is a doublet involving a γ ray from another residual nucleus. Furthermore, the theoretical work of Horie and Ogawa[13] could not provide an explanation for the existence of a long lived level at 2519 keV in ^{52}Ti.

Another argument favoring the identification of the 1469-keV γ ray, along with the coincident 1050-keV γ ray, with ^{52}V is that their energies are consistent with energy differences between observed levels in ^{52}V. As shown in Fig. 1, the ground state of ^{52}V has been found[7] to be 3^+ from β-decay studies, while observations[6] on γ rays following neutron capture in ^{51}V have made 5^+ the most likely J^π assignment for the level at 23 keV. Catala *et al.*[5] have observed a weak $l=3$ ^{51}V(d, p)^{52}V stripping transition to a level at 1492 keV excitation, allowing a maximum J^π of 7^+. The observed 1469-keV γ ray has the correct energy for a transition between the 1492- and 23-keV levels in ^{52}V.

The 1050-keV γ-ray peak that is coincident with the 1469-keV γ ray then suggests an yrast level in ^{52}V at an energy that is essentially equivalent to that of another weakly excited level observed by Catala *et al.* at 2541 keV. The 1050-keV doublet, in addition, exhibits a broad excitation function which is consistent with both the (^{7}Li, $3n$) and (^{7}Li,$p2n$) reactions.[12] The identification of the 1050-1469-keV γ-ray cascade with ^{52}V is also consistent with the present ^{6}Li + ^{48}Ca excitation results and empirical reaction calculations.[12]

The lifetime observed in the present experiment with the 1469-keV γ ray is thus properly assigned to the 2541-keV level in ^{52}V as shown in Fig. 1, while the decay curve observed for the 1050-keV γ-ray peak is consistent with a mixture of this lifetime and the lifetime of the (6^+) state in ^{52}Ti. The experimental ratio data for the 1469-keV γ ray are shown in the lower part of Fig. 3. A mean lifetime of $\tau = 7.7 \pm 0.5$ psec for the 2541-keV level in ^{52}V was obtained from the least squares fit.

The theoretical work of Horie and Ogawa[13,14] for the $N=29$ nuclei resulted in a level scheme for ^{52}V that is in essential agreement with the above experimental interpretation. The yrast levels in their theory, through which the fusion-evaporation cascade γ rays would proceed, are a 9^+ state at 2677 keV, a 7^+ state at 1590 keV, and a low lying 5^+ state. These energies as well as the theoretical $9^+ \to 7^+$ $B(E2)$ value are in fairly good agreement with the experimental ^{52}V levels shown in Fig. 1 and the experimental lifetime for the 2541-keV (9^+) level. Detailed comparisons will be made in the next section. The agreement with theory adds considerable strength to the above interpretation of the experimental results.

IV. DISCUSSION

The nuclei studied in the present experiment have fairly simple shell-model descriptions assuming a closed ^{48}Ca core. The valence particle configurations are $[(\pi 1f_{7/2})^n \otimes (\nu 2p_{3/2}, 1f_{5/2}, 2p_{1/2})^m]$ where $(n, m) = (2,1)$ for ^{51}Ti, $(3,1)$ for ^{52}V, and $(2,2)$ for ^{52}Ti. At the ^{48}Ca shell closure $(n=0)$, the $\nu 2p_{1/2}$ and $\nu 1f_{5/2}$ orbitals are separated by about 2.0 and 4.0 MeV, respectively, from the $\nu 2p_{3/2}$ orbital which is lowest.[14] Hence the dominant low lying configurations, when n is small, involve only the $\nu 2p_{3/2}$ orbital. At the ^{56}Ni shell closure $(n=8)$ the $\nu 2p_{1/2}$ and $\nu 1f_{5/2}$ orbitals are only about 1.1 and 0.8 MeV, respectively, higher than the $\nu 2p_{3/2}$ orbital[14] which will result in more complex low lying configurations for the nuclei closer to ^{56}Ni.

A striking feature of the yrast energy levels for the $N=29$ nuclei $(m=1)$ ^{51}Ti and ^{52}V as well as the nuclei ^{53}Cr, ^{54}Mn, and ^{55}Fe discussed in our previous work[1] is the near correspondence in excitation energies with the neighboring $N=28$ nuclei. The well known experimental $N=28$ $(\pi 1f_{7/2})^n$ yrast levels are given in Table II along with the $N=29$ yrast levels. This correspondence suggests that the proton-proton correlations are more important than the proton-neutron correlations which lead to a dominant stretched configuration of the type $[(\pi 1f_{7/2})^n J', (\nu 2p_{3/2})]J = J' + \frac{3}{2}$ for the $N=29$ yrast states.

Using these stretched wave functions, the $N=29$ $B(E2)$ values are given simply by $B(E2)[J_i \to J_f] = B(E2)[J_i' \to J_f']$. The theoretical $(1f_{7/2})^n B(E2)[J_i' \to J_f']$ values have been tabulated previously.[10] These calculated $B(E2)$ values are compared with the experimental results in columns 3 and 4 of Table III. For these calculated values, a proton effective charge of $e_p = 2.2$ has been used which gives good agreement with the ^{51}Ti $\frac{15}{2}^- \to \frac{11}{2}^-$, ^{51}Ti $\frac{11}{2}^- \to \frac{7}{2}^-$, ^{52}V $9^+ \to 7^+$, and ^{53}Cr $\frac{7}{2}^- \to \frac{3}{2}^-$ transitions. The four other experimental $B(E2)$ values given in Table III are not in good agreement with the calculation; however, as will be discussed below, the agreement in these cases is not improved by a more exact calculation which takes into account the proton-neutron correlations as well as the additional $\nu 2p_{1/2}$ and $\nu 1f_{5/2}$ orbitals. In the simple stretched description for the $N=29$ yrast levels, the additional proton charge $\delta e_p = 1 - e_p = 1.2$ is 30% larger than the average value $\delta e_p = 0.9$ needed for the $N=28$ nuclei. The additional complexity of the wave functions which is ignored in the stretched scheme is adequately taken into account by a 30% renormalization of the $E2$ effective operator.

More exact calculations for the $N=29$ nuclei have been carried out by Horie and Ogawa.[13,14] They determined the $[(\pi 1f_{7/2})^n \otimes (\nu 2p_{3/2}, 1f_{5/2}, 2p_{1/2})]$ wave functions assuming empirical single particle energies and effective interactions chosen to give best overall agreement with selected experimental energy levels. The calculated energy levels[14,15] are given in Table II; in all cases the agreement is good. The calculated $B(E2)$ values are given in column 6 of Table III in the form $B(E2) = (Ae_p + Be_n)^2$. If the additional proton effective charge of $\delta e_p = 0.9$ needed for the pure-proton $N=28$ configurations[10] is taken, then an average value of $e_n = \delta e_n = 1.0 \pm 0.3$ is needed to reproduce the ^{51}Ti and ^{52}V $B(E2)$ values. Some of the experimental $B(E2)$ values in ^{53}Cr and ^{55}Fe are still in poor agreement with theory. This neutron effective charge is between the value of $e_n = 0.68 \pm 0.02$ needed for the $(\nu f, p)^n$ $6^+ \to 4^+$ transitions in ^{42}Ca and ^{46}Ca[10,16] and the value of $e_n = 1.70 \pm 0.08$ needed for the $(\nu 1f_{5/2}, 2p)^n$ transitions in the Ni isotopes.[17]

Horie and Ogawa have also carried out calculations for the $N=30$ nuclei.[13] The comparison with ^{52}Ti is discussed below; the comparison with other $N=30$ nuclei has been discussed previously.[1] The calculated excitation energies of the yrast levels in ^{52}Ti are[13,15]: g.s. 0^+, 956 keV 2^+, 2277 keV 4^+, and 3011 keV 6^+. These are in very good agreement with the experimental levels shown in Fig. 1. The 8^+ and 10^+ levels predicted at 4100 and 7226 keV, respectively, have not yet been observed experimentally. The calculated $B(E2)$ values for the $6^+ \to 4^+$ and $2^+ \to 0^+$ transitions are $(3.39e_p + 3.75e_n)^2$ and $(3.15e_p + 5.33e_n)^2$, respectively. Using $\delta e_p = 0.9$ and $\delta e_n = 1.0$, the $B(E2)[6^+ \to 4^+] = 104$ e^2fm^4 and the $B(E2)[2^+ \to 0^+] = 128$ e^2fm^4, both of which agree within the uncertainties with the experimental values given in Table I.

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