I. INTRODUCTION

The systematic behavior of the low-energy structures of neutron-rich nuclides in the vicinity of doubly magic $^{48}$Ca has revealed a strong interplay between the proton and the neutron orbitals near the Fermi surface. The monopole migration of the $\nu f_{5/2}$ orbital with the changing occupancy of the $\pi f_{7/2}$ orbital produces a significant subshell gap at $N = 32$ for the even-even $^{24}$Cr [1,2], $^{22}$Ti [3], and $^{20}$Ca [4] isotopes. Shell-model results obtained with the new effective interaction labeled GXPF1 [5,6], which is based on effective two-body matrix elements with some replacement with the labeled GXPF1 [5,6], which is based on effective two-body matrix, were shown to reproduce well the systematic variation of the low-energy levels of the even-even nuclides in the vicinity of doubly magic $^{48}$Ca has been attributed to the deformation-driving $\nu g_{9/2}$ orbital approaching the Fermi surface in these neutron-rich isotopes. Indeed, in $^{59}$Cr$_{35}$ (discussed below), there is evidence for a low-energy $9/2^+$ isomeric state that has been proposed as an oblate-deformed Nilsson orbital originating from the spherical $\nu g_{9/2}$ orbital [14]. Therefore we have extended our previous studies of the $\beta$-decay of neutron-rich $^{22}$Ti [15] and $^{23}$V [16] isotopes to include $^{57}$Ti and $^{59}$V to further investigate the dynamic nature of the neutron $pfg$ orbitals with filling of the $\pi f_{7/2}$ orbital.

Scant data are available in the literature regarding the $\beta$-decay properties of either $^{57}$Ti or $^{59}$V. Three previous measurements of the $\beta$-decay half-life of $^{57}$Ti have been reported: Dörrler et al. [17] quote a value of $56 \pm 20$ ms; Sorlin et al. [18], $67 \pm 25$ ms; and Ameil et al. [19], $180 \pm 30$ ms. No information is available on excited states in the daughter $^{57}$V; however, the $\beta$-decay of the $^{57}$V has been well characterized [16]. The $\beta$-decay of $^{59}$V was studied previously by Sorlin et al. [18] and, in addition to deducing a decay half-life of $75 \pm 7$ ms, they observed two $\beta$-delayed $\gamma$ rays with energies of 102 and 208 keV. These same two $\gamma$ rays, as well as a third with energy 193 keV, were assigned to the decay of a microsecond isomer in $^{59}$Cr [20]. Although Grzywacz et al. [20] originally identified the 208-keV transition as the isomeric transition in $^{59}$V, the subsequent $\beta$-decay work suggested that the 193-keV transition directly depopulates the isomeric $9/2^+$ state, which lies only 503 keV above the $^{59}$Cr ground state. Freeman et al. [14] populated excited states in $^{59}$Cr by a fusion-evaporation reaction and observed five $\gamma$ rays; those at 102 and 208 keV, discussed above, and three more at 256, 518, and 813 keV. The last transition, with energy
813 keV, had the highest relative intensity and was assigned to the direct population of the proposed $9/2^+$ isomeric state. Coincidences across the isomer were not observed because of the long lifetime ($\sim 100 \mu s$) of this state.

II. EXPERIMENTAL TECHNIQUE

The $\beta$-decay properties of $^{57}$Ti and $^{59}$V were studied through the use of the experimental facilities at the National Superconducting Cyclotron Laboratory (NSCL) at Michigan State University (MSU). A 140-MeV/nucleon $^{86}$Kr$^{34+}$ beam was produced by the coupled cyclotrons at the NSCL. The average beam current on target was 15 pNA. The $^{86}$Kr was produced by the coupled cyclotrons at the NSCL. The primary beam was fragmented in a 376-mg/cm$^2$-thick Be target located at the object position of the A1900 fragment separator [21]. The secondary fragments of interest were selected in the A1900 by use of a 330-mg/cm$^2$ Al degrader and 1% momentum slits; both were located at the intermediate image of the device.

The fully stripped fragments were implanted in a double-sided Si microstrip detector (DSSD) with thickness 1470 $\mu$m that is part of the NSCL $\beta$-counting system [22]. Fragments were unambiguously identified by a combination of multiple energy-loss signals and time of flight. The fragment particle identification spectrum obtained with A1900 magnetic rigidities of $B\rho_1 = 4.239$ Tm and $B\rho_2 = 3.944$ Tm is shown in Fig. 1. A total of $1.92 \times 10^5$ $^{57}$Ti ions and $5.40 \times 10^5$ $^{59}$V ions were implanted into the DSSD.

Fragment-$\beta$ correlations were established in software by the requirement of a high-energy implantation event in a single pixel of the DSSD followed by a low-energy $\beta$ event in the same or any of the nearest eight neighboring pixels. The differences between the absolute time stamps of correlated $\beta$ and implantation events were histogrammed to generate a decay curve. To suppress background, implantation events were rejected if they were not followed by a $\beta$ event within 1 s or if they were followed by a second implantation within the same 1-s time period. The $\beta$-detection efficiency for both the $^{57}$Ti and $^{59}$V decays was $\sim 30\%$.

Delayed $\gamma$ rays were detected by 12 Ge detectors from the MSU segmented germanium array [23] arranged around the $\beta$-counting system, giving a total peak detection efficiency of 5.3% at 1 MeV. The energy resolution for each of the Ge detectors was measured to be $\sim 3.5$ keV for the 1.3-MeV $\gamma$-ray transition in $^{60}$Co.

III. RESULTS

A. $^{57}$Ti

The $\beta$-delayed $\gamma$-ray spectrum for $^{57}$Ti in the range 0–2.5 MeV is given in Fig. 2. The spectrum includes all $\gamma$ rays detected within 1 s of the implantation of a $^{57}$Ti ion. Six $\gamma$ rays, including two prominent ones located at 268 and 692 keV, are known from the daughter decay of $^{57}$V [16]. The $\gamma$ rays attributed to the decay of $^{57}$Ti are listed in Table I. There were

![FIG. 1. (Color online) (a) Particle identification spectrum and (b) fragment-$\beta$ correlated particle identification spectrum.](image)

![FIG. 2. $\beta$-delayed $\gamma$-ray spectrum from the decay of $^{57}$Ti in the ranges (a) 0–0.4 MeV and (b) 0.4–2.5 MeV for events occurring within 1 s of an implanted $^{57}$Ti ion. The filled circles indicate peaks corresponding to transitions previously assigned to the daughter $^{57}$V decay.](image)
no γ rays that could be associated with the low-energy levels of 56V; therefore it does not appear that there is a significant delayed neutron branch to excited levels in 56V.

The half-life of 57Ti deduced from a fit of the fragment-β-decay curve presented in Fig. 3(a) is 98 ± 5 ms. The decay curve was fitted considering the exponential decay of the parent, exponential growth, and decay of the daughter 57V, and a linear background term. The half-life of the daughter 57V was taken to be 350 ms [16]. Fragment-β-γ-decay curves were also analyzed for each of the γ-ray transitions assigned to 57Ti. Examples for the more intense γ rays with energies of 175, 1579, and 1861 keV are also shown in Fig. 3. The γ-gated decay curves were fitted with an exponential decay and a linear background component. The deduced half-life values were consistent, within errors, with the half-life determined from the fragment-β-decay curve, verifying their assignments to the decay of 57Ti. Previous measurements of the 57Ti half-life include values of 67 ± 25 ms [18], 180 ± 30 ms [19], and 56 ± 20 ms [17]. However, these measurements isolated 57Ti in very small quantities. Based on the present half-life results, a value of 98 ± 5 ms for the half-life of 57Ti has been adopted.

The proposed low-energy level scheme of 57V populated following the β-decay of 57Ti is presented in Fig. 4. All of the proposed levels follow from γγ coincidence relationships. Based on the efficiency-corrected intensity ratios between the 113- and 175-keV peaks in the 1579- and 1861-keV γ-gated coincidence spectra (see Fig. 5), the 113- and 175-keV transitions are consistent with the 1579- and 1861-keV levels in 57V.
transitions were placed in parallel. Inspection of the 1923-keV coincidence gated spectrum suggests that this transition should be placed as directly feeding the 113-keV state. The absence of peaks at both 113 or 175 keV in the 1732-keV gated coincidence spectrum established the 1732-keV level. There is a coincidence observed between the 744- and 1732-keV lines, and the former transition has been placed as depopulating a level at 2476 keV. The presence of both the 113- and 175-keV transitions in the coincidence spectra for the 1579- and 1861-keV \( \gamma \) rays suggests that there is an unobserved 62-keV \( \gamma \) ray depopulating the 175-keV state. Such a low-energy transition would have been below the hardware thresholds set for the Ge detectors. The order of the 62- and 113-keV transitions is determined by the 1923-keV \( \gamma \) ray, which populates the level at 2036 keV and is in coincidence with only the 113-keV \( \gamma \) ray.

The apparent \( \beta \) feedings in \( ^{57}\text{V} \) were determined from differences in absolute \( \gamma \)-ray intensities for transitions into and out of each level. The ground-state feeding was deduced by use of the additional knowledge of the total number of \( ^{57}\text{Ti} \) parent nuclei implanted into the DSSD. The \( \beta \)-branching ratios, as well as the deduced apparent log \( ft \) values, are given in Fig. 4. The experimental \( Q_\beta \) value of 10.6 \( \pm \) 0.6 MeV was deduced from data in Ref. [24]. The large \( Q \)-value window and limitations on the detection of \( \gamma \) rays with absolute intensities below 1% permit only limited interpretations by use of the apparent log \( ft \) values. However, a significant portion of the apparent \( \beta \) feeding directly populates the ground state of \( ^{57}\text{V} \). Further details regarding the feeding patterns to levels in \( ^{57}\text{V} \) are left for the discussion.

B. \( ^{59}\text{V} \)

The \( \beta \)-delayed \( \gamma \)-ray spectrum in the energy range of 0–3 MeV for those events observed within 1 s of the implantation of a \( ^{59}\text{V} \) ion into the DSSD is given in Fig. 6. Numerous \( \gamma \)-ray transitions are observed in this spectrum, and those assigned to the decay of \( ^{59}\text{V} \) are listed in Table II. Other \( \gamma \) rays present

TABLE II. Energies and absolute intensities of delayed \( \gamma \) rays assigned to the decay of \( ^{59}\text{V} \). The initial and final states for those transitions placed in the \( ^{59}\text{Cr} \) level scheme are also indicated.

<table>
<thead>
<tr>
<th>Energy (keV)</th>
<th>( I_{abs} ) (%)</th>
<th>Initial state (keV)</th>
<th>Final state (keV)</th>
<th>Coincident ( \gamma ) rays (keV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>102.0 ( \pm ) 0.4</td>
<td>21 ( \pm ) 2</td>
<td>310</td>
<td>208</td>
<td>208, 426, 491, 606, 977, 1031, 1056, 1530</td>
</tr>
<tr>
<td>207.8 ( \pm ) 0.4</td>
<td>41 ( \pm ) 3</td>
<td>208</td>
<td>0</td>
<td>102, 317, 372, 491, 592, 606, 708, 841, 977, 1031, 1056, 1222</td>
</tr>
<tr>
<td>317.3 ( \pm ) 0.4</td>
<td>3.0 ( \pm ) 0.4</td>
<td>525</td>
<td>208</td>
<td>208, 841</td>
</tr>
<tr>
<td>371.7 ( \pm ) 0.5</td>
<td>1.6 ( \pm ) 0.3</td>
<td>1341</td>
<td>915</td>
<td>102, 208, 606, 1530</td>
</tr>
<tr>
<td>425.5 ( \pm ) 0.4</td>
<td>1.7 ( \pm ) 0.3</td>
<td>800</td>
<td>310</td>
<td>102, 208</td>
</tr>
<tr>
<td>463.1 ( \pm ) 0.4</td>
<td>1.7 ( \pm ) 0.2</td>
<td>800</td>
<td>208</td>
<td>208</td>
</tr>
<tr>
<td>490.8 ( \pm ) 0.5</td>
<td>2.3 ( \pm ) 0.4</td>
<td>915</td>
<td>310</td>
<td>102, 208, 426</td>
</tr>
<tr>
<td>592.4 ( \pm ) 0.4</td>
<td>4.2 ( \pm ) 0.3</td>
<td>915</td>
<td>208</td>
<td>208</td>
</tr>
<tr>
<td>606.0 ( \pm ) 0.4</td>
<td>6.4 ( \pm ) 0.4</td>
<td>915</td>
<td>208</td>
<td>208</td>
</tr>
<tr>
<td>707.6 ( \pm ) 0.5</td>
<td>1.1 ( \pm ) 0.3</td>
<td>800</td>
<td>0</td>
<td></td>
</tr>
<tr>
<td>784.1 ( \pm ) 0.4</td>
<td>1.8 ( \pm ) 0.3</td>
<td>800</td>
<td>0</td>
<td></td>
</tr>
<tr>
<td>799.9 ( \pm ) 0.5</td>
<td>1.1 ( \pm ) 0.3</td>
<td>800</td>
<td>0</td>
<td></td>
</tr>
<tr>
<td>823.2 ( \pm ) 0.6</td>
<td>1.1 ( \pm ) 0.3</td>
<td>823.2 ( \pm ) 0.6</td>
<td>208, 463, 1222</td>
<td></td>
</tr>
<tr>
<td>841.4 ( \pm ) 0.4</td>
<td>2.7 ( \pm ) 0.3</td>
<td>1366</td>
<td>525</td>
<td>208, 317</td>
</tr>
<tr>
<td>879.9 ( \pm ) 0.5</td>
<td>3.0 ( \pm ) 0.4</td>
<td>1366</td>
<td>102, 208</td>
<td></td>
</tr>
<tr>
<td>959.9 ( \pm ) 0.4</td>
<td>2.2 ( \pm ) 0.3</td>
<td>1056</td>
<td></td>
<td></td>
</tr>
<tr>
<td>977.2 ( \pm ) 0.5</td>
<td>1.4 ( \pm ) 0.2</td>
<td>1532</td>
<td>102, 208</td>
<td></td>
</tr>
<tr>
<td>1030.8 ( \pm ) 0.4</td>
<td>2.4 ( \pm ) 0.3</td>
<td>1341</td>
<td>310</td>
<td>102, 208</td>
</tr>
<tr>
<td>1056.0 ( \pm ) 0.4</td>
<td>2.5 ( \pm ) 0.3</td>
<td>1366</td>
<td>310</td>
<td>102, 208, 880</td>
</tr>
<tr>
<td>1157.8 ( \pm ) 0.5</td>
<td>0.8 ( \pm ) 0.2</td>
<td>1366</td>
<td>208</td>
<td></td>
</tr>
<tr>
<td>1206.5 ( \pm ) 0.6</td>
<td>0.6 ( \pm ) 0.2</td>
<td>1532</td>
<td>102, 208</td>
<td></td>
</tr>
<tr>
<td>1222.1 ( \pm ) 0.4</td>
<td>2.5 ( \pm ) 0.3</td>
<td>1532</td>
<td>102, 208</td>
<td></td>
</tr>
<tr>
<td>1529.6 ( \pm ) 0.5</td>
<td>1.0 ( \pm ) 0.3</td>
<td>1529.6 ( \pm ) 0.5</td>
<td>102, 208</td>
<td></td>
</tr>
<tr>
<td>1593.4 ( \pm ) 0.5</td>
<td>2.2 ( \pm ) 0.4</td>
<td>2509</td>
<td>915</td>
<td></td>
</tr>
<tr>
<td>1680.9 ( \pm ) 0.5</td>
<td>1.9 ( \pm ) 0.3</td>
<td>2089.6 ( \pm ) 0.5</td>
<td>0.9 ( \pm ) 0.2</td>
<td></td>
</tr>
<tr>
<td>2198.7 ( \pm ) 0.5</td>
<td>0.5 ( \pm ) 0.2</td>
<td>2509</td>
<td>310</td>
<td></td>
</tr>
<tr>
<td>2375.0 ( \pm ) 0.6</td>
<td>0.8 ( \pm ) 0.2</td>
<td>2601.3 ( \pm ) 0.6</td>
<td>1.2 ( \pm ) 0.2</td>
<td></td>
</tr>
</tbody>
</table>

\( a \)Possible \( \beta \)-delayed neutron branch to excited levels in \( ^{59}\text{Cr} \). See text for details.
included those from the decay of the $^{59}$V daughter, which are
discussed in more detail below, and of the $^{59}$Mn granddaughter,
which were readily identified from the decay curves gated
on individual $\gamma$-ray transitions. Of the $\gamma$ rays listed in Table
II, those with energies of 102 and 208 keV were observed
in previous studies of the decay of excited states in $^{59}$Cr
[14,18,20].

In Fig. 7 are presented the fragment-$\beta$-decay curves
gated on the 102- and 208-keV $\gamma$-ray transitions assigned
to $^{59}$V decay. A half-life of $97 \pm 2$ ms was deduced for
the ground-state decay of $^{59}$V. Other decay curves gated
on delayed transitions assigned to the decay of $^{59}$V re-
vealed half-lives consistent within the statistical error of this
result.

The proposed level scheme for $^{59}$Cr populated through
the $\beta$-decay of $^{59}$V is introduced in Fig. 8. The $\gamma$ rays with
energies of 102 and 208 keV were identified and placed into
a level scheme previously [18]. The placement of these two $\gamma$
rays in series, with the lowest excited state at an energy of
208 keV, was confirmed by the $\gamma\gamma$ coincidence spectra
obtained in this experiment and shown in Fig. 9. Such a
placement refutes the findings presented in Ref. [14], in which
the 102- and 208-keV transitions are reversed in the level
scheme. In particular, the coincidence spectra gated on the
317-,$592$-, and 708-keV transitions show only the 208-keV
transition, and not a transition with an energy of $102$ keV.
Because the 208- and 102-keV transitions are in cascade,
the 208-keV $\gamma$ ray must directly populate the $^{59}$Cr ground
state. Of the other $\gamma$ rays assigned to the decay of $^{59}$V, most
feed directly the levels at either 208 or 310 keV, and these
coincidence relationships helped define the proposed level
structure above 300 keV. The proposed state at 525 keV is
shown as a tentative placement because the order of the
371- and 841-keV transitions could not be determined explicitly.
A similar situation exists for the 1532-keV state, which is based
on the 208–1222 coincidence, although the ordering of the

977- and 1222-keV $\gamma$ rays could not be resolved from
the available data. The tentative level at 2509 keV is the
only proposed level not based on coincidences; energy-sum
relationships were used to place the 977-, 1593-, and 2199-keV
$\gamma$ rays as depopulating the proposed 2509-keV state.

The log $ft$ values and $\beta$-decay branching ratios were not
deduced because there are still a number of unassigned $\gamma$-ray
transitions. However, it should be noted that, based on the
total number of $\beta$-decays observed and the summed intensities
of $\gamma$-ray transitions that directly populate the ground state,
there is apparent direct $\beta$ feeding to the ground state of
$^{59}$Cr.

Sorlin et al. [18] had previously proposed spin and parity
assignments of $1/2^-$, $3/2^-$, and $5/2^-$ for the ground and first
two excited states of $^{59}$Cr, respectively. The spin and parity
of the 310-keV level are based on the M2 character of the
193-keV isomeric $\gamma$ ray that depopulates the proposed $9/2^+$
level at 503 keV [20]. The tentative $1/2^-$ and $3/2^-$ spin
and parity assignments for the ground and first excited states
are supported in this measurement. If the spin assignments
were reversed, the 102-keV transition would have E2 multipolarity,
and a lifetime of the order of a few microseconds would be
expected based on Weisskopf estimates. However, no evidence
of a long lifetime (greater than 200 ns) for the 102-keV $\gamma$-ray
transition was found.

It should be noted that a small $\beta$-delayed neutron branch
cannot be ruled out for the decay of $^{59}$V. The 880- and
1056-keV $\gamma$-ray transitions assigned to levels in $^{58}$Cr [16]
have also been observed in the delayed $\gamma$-ray spectrum for
$^{59}$V as displayed in Fig. 6. A 1056-keV $\gamma$ ray was observed in
coincidence with the 102- and 208-keV $\gamma$ rays assigned to the

FIG. 7. Decay curves for $^{59}$V showing fragment-$\beta$ correlations
with an additional requirement of a coincident $\gamma$ ray with an energy
of (a) 102 keV and (b) 208 keV. The decay curves were fitted with an
exponential function with linear background.

FIG. 8. Proposed $^{59}$Cr level scheme populated following the
decay of $^{59}$V. The number in brackets following a $\gamma$-ray transition
energy is the absolute $\gamma$-ray intensity. The $Q$ value was deduced from
data in Ref. [24]. Observed coincidences are represented as filled
circles.
decay of $^{59}$V. Based on the absolute intensity of the 880-keV $\gamma$ ray, which is not observed in coincidence with $\gamma$ rays assigned to $^{59}$V, the $\beta$-delayed neutron branch to levels in $^{58}$V that directly feed the $2^+$ state is deduced to be $\sim$3%; this should be considered a lower limit.

C. $^{59}$Cr

The first adopted half-life of $^{59}$Cr, 740 $\pm$ 240 ms [25,26], was obtained from an average of the $\gamma$-gated half-lives of 1.0 $\pm$ 0.4 s and 0.6 $\pm$ 0.3 s for the 1238- and 112-keV $\gamma$ rays, respectively, weighted by their relative intensities. A subsequent measurement of the $\beta$-decay of $^{59}$Cr by Dörfler et al. [17] resulted in a half-life value of 460 $\pm$ 46 ms. We have deduced a new half-life of $^{59}$Cr based on a decay curve gated on the 1238-keV $\gamma$ ray assigned to the granddaughter $^{59}$Mn, as shown in Fig. 10(a). The curve in Fig. 10(a) was fitted considering the exponential growth and decay of $^{59}$Cr as well as a linear background. A half-life of the $^{59}$V parent was taken to be the present value of 97 ms. The deduced half-life of $^{59}$Cr was 1050 $\pm$ 90 ms.

This new value of the $^{59}$Cr half-life was used to fit the daughter contribution to the $^{59}$V fragment- $\beta$-decay curve, given in Fig. 10(b). Here, the fit function included exponential decay of the $^{59}$V parent, exponential growth and decay of the $^{59}$Cr daughter with a fixed half-life of 1050 ms, and a linear background. A half-life value of 95 $\pm$ 3 ms was deduced for $^{59}$V, in agreement with the adopted half-life of 97 $\pm$ 2 ms based on fits of the fragment- $\beta$-$\gamma$-decay curves in Fig. 7.

The new half-life value of 1050 $\pm$ 90 ms for the $^{59}$Cr $\beta$-decay agrees, within errors, with the first adopted half-life of $^{59}$Cr, which was deduced from the decay characteristics of daughter $\gamma$ rays [25,26]. Disagreement with the half-life value quoted by Dörfler et al. [17] might be attributed to the limited $\beta$-$\gamma$ statistics obtained in this earlier measurement.

A proposed level scheme for $^{59}$Mn populated following the $\beta$-decay of $^{59}$Cr is given in Fig. 11. $\gamma$-$\gamma$ coincidence spectra used for $\gamma$-ray placement in $^{59}$Mn are presented in Fig. 12. The 662- and 1238-keV $\gamma$ rays were found to be in coincidence. A mutual coincidence was not observed for the 112- and 1238-keV transitions, and both are placed as directly feeding the $^{59}$Mn ground state.
β-DECAY OF ODD-Α 57Ti AND 59V

IV. DISCUSSION

Calculations of the β-decay of 57Ti to low-energy levels in 57V were carried out with the pf shell-model interaction GXPF1 [5,6] and the codes OXBASH [27] and CMICHSM [28].

The GXPF1 interaction is known to overpredict the energy gap between the neutron f5/2 and p1/2 orbitals at N = 34 [8], and a new interaction GXPF1A has been introduced that involves modifications to the T = 1 two-body matrix elements as a means for better reproducing the yrast energy spectrum of 56Ti [7,10]. The β-decay properties of neutron-rich 22Ti [15] and 23V [16] were successfully reproduced with the GXPF1 interaction, and therefore we elected again to apply the GXPF1 interaction for the shell-model calculations reported here. The goal of selecting the GXPF1 interaction was to further identify potential deficiencies in the GXPF1 interaction related to the β-decay matrix elements.

The ground-state spin and parity of 57Ti are expected to be 5/2−, based on the shell-model results obtained with the GXPF1 interaction. Such a spin and parity assignment for the ground state is consistent with the odd neutron in 57Ti occupying the v f5/2 orbital. Previous results with the GXPF1 interaction have shown that, for 55Ti, the ground-state spin and parity are expected to be 1/2−, suggesting that the effective single-particle energy of the vp1/2 orbital is lower than that for the v f5/2 orbital. The first excited state in 57Ti is calculated to lie at an energy of 422 keV, with spin and parity 1/2−. The calculations of the β-decay properties of 57Ti have therefore been carried out assuming 5/2− spin and parity for the ground state.

The calculated β-decay of 57Ti to levels in 57V is presented in Fig. 13. Considering that the lower detection limit for absolute intensities in the 57Ti β-decay was ∼0.7%, the experimental and calculated β-decay properties agree quite well. Direct β feeding to the 57V ground state is estimated at 44%, which compares favorably with the deduced ground-state β branch of 54% ± 3%. The shell-model results also predict a significant amount of β-decay feeding to four states above 1500 keV in 57V, which correspond well with the observed apparent β branchings.

Some correspondence between the proposed low-energy-level structure of 57V fed in β-decay and that predicted by the shell-model calculations is apparent. There is nearly a 1.5-MeV gap between the triplet of levels observed experimentally near the 57V ground state and the next proposed level at 1732 keV. The shell-model results obtained with GXPF1 include a shell closure at N = 34 [5], leading to the low-level density below 1.7 MeV in 57V, as seen in Fig. 13.
The low-energy triplet most likely corresponds to the lowest three levels with spins and parities of \(7/2^-\), \(5/2^-\), and \(3/2^-\) resulting from the shell-model calculations with the GXPF1 interaction. The spread of the lowest three calculated levels in \(^{57}\text{V}\), compared with the new experimental results, is within the limits of accuracy of the GXPF1 interaction, which we obtained by fitting 699 levels in \(87\text{pf}\) nuclei with a root-mean-square deviation of 168 keV [6]. A tentative spin and parity assignment of \(3/2^-\) for the ground state of \(^{57}\text{V}\) was initially proposed by Sorlin et al. [29], based on the characteristics of the \(\beta\)-decay into levels of \(^{57}\text{Cr}\) compared with quasiparticle random-phase approximation calculations. Later, the \(^{57}\text{V} \rightarrow \text{Cr}\) ground-state branch was remeasured and resulted in a value of 21% [16]. A comparison of the \(^{57}\text{V}\) \(\beta\)-decay characteristics with the results of GXPF1 shell-model calculations favored a spin and parity of either \(5/2^-\) or \(7/2^-\) for the ground state of \(^{57}\text{V}\). The significant direct \(\beta\)-decay branch to the \(^{57}\text{V}\) ground state would favor a \(7/2^-\) spin and parity assignment based on the shell-model calculations. Such a spin and parity assignment to the ground state of \(^{57}\text{V}\) would suggest a less deformed (slightly oblate) structure based on the potential-energy surfaces calculated for the odd-\(A\)\(\text{V}\) isotopes in Ref. [18].

The low-energy structure of \(^{59}\text{Cr}\) proposed here differs from that in Ref. [14] only in the order of the \(\gamma\)-ray cascade, including the 208- and 102-keV transitions. The tentative spin and parity assignment of \(5/2^-\) for the ground state of the \(^{59}\text{V}\) parent is taken from Sorlin et al. [18]. The low-energy-level scheme from the shell-model calculations in the full \(pf\) shell with the GXPF1 interaction is given by Freeman et al. [14] and shows only seven negative-parity levels below 1.6 MeV. The level structure of \(^{59}\text{Cr}\) proposed in Fig. 8 has eight excited levels below 1.6 MeV. Although not all are directly populated in \(\beta\)-decay, based on the tentative \(5/2^-\) spin and parity assignment to the \(^{59}\text{V}\) \(\beta\)-decaying state and the average number of cascade \(\gamma\) rays of \(\approx 2\), all of these excited levels are most likely of negative parity with spins \(\leq 9/2\). No evidence for a 813-keV \(\gamma\) ray as observed by Freeman et al. and placed as directly populating the proposed \(9/2^-\) level in \(^{59}\text{Cr}\) at 503 keV was observed. However, this is not surprising because direct \(\beta\) feeding to such a state in \(^{59}\text{Cr}\) would be highly forbidden. Furthermore, no evidence for a transition at 518 keV, which was tentatively placed as depopulating a proposed \(7/2^-\) state at 828 keV in \(^{59}\text{Cr}\) [14], was observed. The absence of a crossover \(E2\) \(\gamma\)-ray transition between the proposed \(5/2^-\) state at 310 keV and the \(^{59}\text{Cr}\) ground state is corroborated by the shell-model calculations results obtained with the GXPF1 interaction.

The presence of the \(9/2^+\) level at low energy in \(^{59}\text{Cr}\) is suggestive of deformation. Freeman et al. [14] proposed moderate oblate deformation (\(\beta_2 \sim -0.2\)) based on comparisons of the low-energy structure with the Nilsson model. Such an interpretation is not altered by the reordering of the 208- and 102-keV \(\gamma\)-ray transitions. Indeed, as Freeman et al. note, low-energy states with spin and parities \(3/2^-\) and \(5/2^-\) can be readily generated by single-neutron excitations into states with spherical \(v_{5/2}\) parentage if oblate deformation is considered.

**V. SUMMARY**

Details regarding the \(\beta\)-decay properties of \(^{57}\text{Ti}\) and \(^{59}\text{V}\) were reported. New half-life values of \(98 \pm 5\) ms for \(^{57}\text{Ti}\) and \(97 \pm 2\) ms for \(^{59}\text{V}\) were deduced from \(\beta\)-decay curves gated on known \(\gamma\)-ray transitions. A new half-life value of \(1050 \pm 90\) ms was also deduced for the daughter \(^{59}\text{Cr}\) \(\beta\)-decay, again based on fitting of the \(\gamma\)-gated \(\beta\)-decay curves. The low-energy-level structures of the daughter nuclides \(^{57}\text{V}\) and \(^{59}\text{Cr}\) were compared with shell-model results calculated in the full \(pf\) shell by use of the GXPF1 interaction. The three lowest-energy states in \(^{57}\text{V}\) reside within 200 keV of the ground state, whereas the next group of excited states observed experimentally lie more than 1.5 MeV above the \(^{57}\text{V}\) ground state. Some correspondence with the shell-model results were revealed, especially between the energies and \(\beta\) branchings to the three lowest-energy states in \(^{57}\text{V}\). The low-energy-level structure observed for \(^{59}\text{Cr}\) appears more complicated than that predicted by shell-model calculations. The \(9/2^+\) spin and parity assignment previously made to the 503-keV level suggests that the \(v_{5/2}\) shell-model orbital has influence, even at low energy, in the neutron-rich \(^{59}\text{Cr}\) nuclides. Both \(^{57}\text{V}\) and \(^{59}\text{Cr}\) show evidence of oblate deformation near the ground state.

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