Band termination in the $N = Z$ Odd-Odd Nucleus $^{46}$V

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High spin states in the odd-odd $N = Z$ nucleus $^{46}$V have been identified. At low spin, the $T = 1$ isobaric analogue states of $^{46}$Ti are established up to $I^* = 6^+$. Other high spin states, including the band terminating state, are tentatively assigned to the same $T = 1$ band. The $T = 0$ band built on the low-lying $3^+$ isomer is observed up to the $1f_{7/2}$-shell termination at $I^* = 15^+$. Both signatures of a negative parity $T = 0$ band are observed up to the terminating states at $I^* = 16^-$ and $I^* = 17^-$, respectively. The structure of this band is interpreted as a particle-hole excitation from the $1d_{5/2}$ shell. Spherical shell model calculations are found to be in excellent agreement with the experimental results.

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In the last few years, the study of $1f_{7/2}$-shell nuclei has gained renewed interest due to dramatic advances in experimental and theoretical techniques. Close to the middle of the $f_{7/2}$ shell, nuclei show strong deformation near the ground state. At high spin, the interplay between single particle and collective behaviour is manifested in backbending and band termination phenomena. The $N = Z = 24$ nucleus $^{46}$Cr has the maximum number of valence particles to develop deformation and is considered the best rotor in this shell with a deformation parameter of $\beta \approx 0.26$. As one moves away from $^{48}$Cr, the collective behaviour is less pronounced, shell effects are more evident and nuclei evolve towards a spherical shape. The $f_{7/2}$-shell nuclei thus provide an excellent opportunity to study the interplay between single particle and collective degrees of freedom as a function of both angular momentum and valence particle number.

Another interesting feature that can be studied in these nuclei as a function of spin and mass number is the pairing interaction. While like-nucleon pairing is of $T = 1$ character, proton-neutron pairs can be coupled to $T = 0$ and $T = 1$. It has been argued that the contribution of both modes of $pn$ pairing decreases rapidly with increasing $|N - Z|$. Of particular interest are, therefore, in this respect, those nuclei which lie on the $N = Z$ line. In the last few years, apart from $^{48}$Cr other even-even $N = Z$ nuclei have been studied up to high spin in this shell, i.e., $^{52}$Fe and very recently $^{44}$Ti. Band-like structures built on the $T = 0$ ground states have been reported in all cases. The competition between $T = 0$ and $T = 1$ pairing modes, however, can be better studied in the odd-odd $N = Z$ nuclei of the $f_{7/2}$ shell, in which ground states have quantum numbers $T = 1 I^* = 0^+$, but the $T = 0$ structures appear at low excitation energies and rapidly become yrast.

The pairing interaction is well known to decrease with increasing spin as the mechanism of generating angular momentum by breaking pairs of valence particles and aligning their spins along the rotational axis could become energetically favored. When all valence particles are aligned with the rotational axis, band terminating states are built. Experimentally, non-collective band-terminating states of natural parity have been reported recently in several nuclei in this shell. Moreover, non-natural parity bands have been observed in many $f_{7/2}$ shell nuclei which correspond to larger deformed structures than those of natural parity. Despite the many recent advances, however, there remains a deficiency in the observation of unnatural parity bands. In many cases the terminating states have not been identified, a fact which becomes crucial for the interpretation of the intrinsic structure.

The most deformed odd-odd self-conjugate nuclei in the $f_{7/2}$ shell are $^{46}$V and $^{50}$Mn, with one proton-neutron pair subtracted or added to $^{48}$Cr, respectively. In a recent work, high spin states in $^{50}$Mn have been reported for the first time. The g.s. $T = 1$ band, isobaric analogue of the g.s. band in $^{50}$Cr, has been reported up to the $4^+$ state, while the $T = 0$ yrast band has been observed up to the band terminating $15^+$ state.

In this work we report the first observation of high spin states in the odd-odd $N = Z$ nucleus $^{46}$V. The $T = 1$ iso-
baric analogue states of 46Ti are established up to spin 6+. The energetically favoured $T = 0$ band built on the isomeric $3^+$ state is extended up to its $f_{7/2}$-shell terminating 15$^+$ state. Both signatures of another $T = 0$ band of negative parity are observed up to the band termination. The intrinsic structure of this band is interpreted as $(d_{5/2}^{-1}(p_f)^7$ configuration. This is the first time that both signatures of an unnatural parity band are observed up to the band termination in this mass region. Very few states were known previously in 46V. In particular, the highest state tentatively reported by Poletti et al. was the $J = 9^+$ at 3094 keV which we confirm. At the same time of this work, other two groups have studied 46V, at low $\alpha$ and high spins. We agree in general with their observations and report several more new levels and transitions to the scheme of 46V which are crucial for the interpretation of the underlying structures.

High spin states in 46V have been populated via the 28Si$(^{24}\text{Mg,}\alpha p\pi \gamma)$ reaction, with a 100 MeV $^{24}$Mg beam provided by the XTU Tandem Accelerator of the Legnaro National Laboratory. The target consisted of 0.4mg/cm$^2$ of 28Si (enriched to 99.9%). Gamma rays were detected with the GASP array, comprising 40 Compton-suppressed HPGe detectors and an 80-element BGO ball which acts as a $\gamma$-ray multiplicity and sum-energy filter. Light charged particles were detected with the ISIS array, consisting of 40 ($\Delta E,E$) Si telescopes. Gain matching and efficiency calibration of the Ge detectors were performed using $^{152}$Eu, $^{56}$Co and $^{60}$Co radioactive sources.

The level scheme of 46V deduced from the present work is shown in Fig. 1. It has been built on the basis of a $\gamma-\gamma-\gamma$-coincidence cube and a $\gamma-\gamma$-matrix constructed from all events in which one proton and one $\alpha$-particle were detected in the ISIS array. In this latter matrix, the kinematical Doppler correction has been performed according to the detection geometry of the charged particles. Gamma-ray spectra obtained from setting coincidence gates in this matrix are shown in Fig. 2. The spin-parity assignments were deduced from the $\gamma$-ray angular distribution, the directional correlation from oriented states (DCO) ratios and from the decay pattern.

The most strongly populated structure in 46V is the positive parity $T = 0$ band A built on the low-lying $3^+$ isomeric state ($T_2 = 1.04$ ms). This band is now extended up to the $15^+$ terminating state, the maximum spin available to 46V in a pure $f_{7/2}$-shell configuration. As happens in 50Mn, where the $T = 0$ bandhead has a spin $J = 5$, while the $pn$ interaction favours in energy the $J = 1$ and $J = 7$ couplings, the strong quadrupole field near the middle of the shell gives rise to a $K^\pi = 3^+$ bandhead for the $T = 0$ yrast band. In the Nilsson scheme this corresponds to a proton and a neutron in the [301]$_3^3$ orbit. The low spin behaviour of the band, including the state $J = 1^+$ at 994 keV, can be interpreted as the smooth alignment of the last proton and neutron in a $T = 0$ coupling.

Bands B and C are also identified as $T = 0$ structures as they have no counterparts in 46Ti. The DCO analysis indicates that states in bands B and C decay by electric quadrupole transitions to the states in band A, which is consistent with the fact that magnetic dipole transitions between $T = 0$ states are hindered.

Above the band termination, a very weak transition feeding the 15$^+$ state is reported. Its intensity is two orders of magnitude weaker than the $15^+ \rightarrow 13^+$ transition which confirms the terminating character of the 15$^+$ state. To build a spin greater than $J = 15$ one proton or one neutron has to be excited to the $f_{7/2}$ subshell which lies about 6 MeV above the $f_{7/2}$. On the basis of DCO analysis we assign $J^\pi = 16^+$ to the state at 11753 MeV.

The $0^+, 2^+, 4^+$ and $6^+$ states of band D in 46V at excitation energies of 0, 915, 2054 and 3365 keV are interpreted as the $T = 1$ isobaric analogues of the $0^+$, $8^+$, $10^+$ and $12^+$ states of 46Ti. These $T = 1$ states were populated very weakly in the present experiment. They decay preferentially by M1 transitions to $T = 0$ states. Other high spin states which decay to band A are tentatively assigned as $T = 1$ states. For the decay of the $(8^+)$ and $(11^+)$ states at 4843 and 7725 keV, the DCO analysis was not conclusive. For the 3702 and 1617 keV transitions from the $12^+(+) = 14^+(+)$ states, respectively, the DCO ratios suggest a dipole character. The tentative parity assignments are based on the decay pattern and the comparison with the level scheme of 46Ti. As will be discussed below, shell model calculations are in general consistent with this assignment.

On the left side of Fig. 1, two very regular band structures are drawn which are interpreted as the two signatures of a negative parity $T = 0$ band. The DCO analysis of the decay transitions of 333, 372, 750, 1198 keV gives ratios consistent with dipole transitions, while for the 451 keV line the obtained DCO ratio suggests a dipole transition of $\Delta J = 0$ type. The parity assignment, based on the decay pattern and on systematics, is also sustained by shell model calculations. Non-natural parity bands in other $f_{7/2}$ nuclei can be described as a $f_{7/2}d_{5/2}^{-1}$ particle-hole excitation. In this picture, the terminating states of both $\alpha = 0$ and $\alpha = 1$ signatures should be $J = 16$ and $J = 17$, respectively, in agreement with what we observe. As stated above, intruder bands of this type have been already observed in odd and even-even nuclei in the $f_{7/2}$ shell, but it is the first time that such a band is observed up to the band termination in both signatures.

We have observed a weak 128-keV transition from the $2^-$ state to a level at 1236 keV which further decays to the $1^+$ level. These two transitions are very weak and therefore no angular correlation analysis was possible. On the basis of the decay pattern and the shell model predictions we tentatively assigned $J^\pi = 0^-$ to the level at 1236 keV.

Both E and F bands are much more regular than the positive parity $T = 0$ band, suggesting more collectivity. A backbending at spin $J \simeq 10$ is evident from Fig. 1. Up to the backbending there is no signature split-
ting, as can be seen on the inset to Fig. 3b. There, the experimental excitation energy normalized to that of a rigid rotor \( (E - 0.05473J(J + 1)) \) for each signature is plotted. At spins higher than \( J = 8 \), the slopes of the curves change, indicating a change of configuration. It can also be observed that both signatures terminate in a favoured way [3]. The \( T = 0 \) nature of the band hinders the magnetic dipole transitions between two signature partner states.

On the right side of Fig. 1, other levels are reported as belonging to a negative parity band G. The tentatively assigned negative parity is based on DCO analysis and decay pattern.

As stated above, SM calculations in the full \( pf \) shell space have been shown to give a very good description of \( \frac{1}{2} \)-shell nuclei. We have performed these calculations to study the positive parity states in \( ^{46}\text{V} \) with the code ANTOINE [12] using the KB3 interaction and the experimental single-particle energies of \( ^{44}\text{Ca} \). The theoretical spectrum for the \( T = 0 \) yrast band and the \( T = 1 \) g.s. band of \( ^{46}\text{V} \) obtained from these calculations is compared with the experimental data in Fig. 3a. The agreement is very good. The B(E2) and B(M1) values for some levels of both \( T = 1 \) and \( T = 0 \) positive parity bands are reported in Table I. Some significative experimental and theoretical branching ratios (BR) are also quoted. The theoretical BR were calculated using the experimental transition energies. The decay properties of both bands are in good agreement with the experimental results.

In the SM framework, the contribution to the energy of each spin state of the different pairing terms can be calculated [3]. We have calculated the expectation value of the pairing correlation energy in perturbation theory, as described in ref. [14] for the \( T = 1 \) isobaric analogue states in \( ^{46}\text{V} \) and \( ^{46}\text{Ti} \). The results are reported in Fig. 4. In the upper part of the figure, the contributions of the \( T = 1 \) pairing terms are plotted for \( ^{46}\text{V} \). The most important contribution arises from the \( pn \ T = 1 \) pairing which decreases with increasing angular momentum. At \( J = 8 \) this pairing mode becomes very small, which is consistent with the fact that the first pair which aligns with the rotational axis is a \( pn \) pair. On the other hand, the contribution of the like-nucleon pairing remains almost constant. The opposite behaviour is found for \( ^{46}\text{Ti} \), as shown in the middle of Fig. 4. The number of valence neutrons in \( ^{46}\text{Ti} \) is twice that of the protons. Therefore, at \( J = 0 \) the \( nn \) pairing contribution is twice that of the protons. At \( J = 2 \) the \( nn \) pairing strength decreases but also the \( pp \) contribution does, although its change is not so marked. At \( J = 4 \) both contributions become almost equal but at \( J = 6 \), while the \( nn \) term remains constant, the \( pp \) contribution decreases by \( \sim 30\% \). This picture would suggest that there is a smooth alignment of both pairs of protons and neutrons with increasing spin. On the other hand, the \( pn \ T = 1 \) pairing strength in \( ^{46}\text{Ti} \) follows the same behaviour of the like-nucleon pairs in \( ^{46}\text{V} \). In the bottom of Fig. 4, the contributions of both \( T = 0 \) and \( T = 1 \) (\( pp, nn \) and \( pn \)) pairing terms are given for \( ^{46}\text{V} \). At low spin, the \( T = 1 \) pairing dominates over the \( T = 0 \). However, by comparing with the \( pn \) contribution in the upper panel, one can conclude that above \( J = 2 \) the \( T = 0 \) \( pn \) pairing is more important than \( T = 1 \) \( pn \) pairing.

The excitation energies at each spin of the \( T = 1 \) analogue states in \( ^{46}\text{V} \) are greater than those in \( ^{46}\text{Ti} \) up to \( J = 6 \). This energy difference could be interpreted as a Coulomb effect due to the fact that when a proton pair aligns in \( ^{46}\text{Ti} \), the Coulomb energy decreases, as has been pointed out in ref. [13]. On the contrary, the alignment of \( pn \) pairs would not affect the Coulomb energy in \( ^{46}\text{V} \). This energy difference is also reproduced by SM calculations. However, SM calculations predict that the excitation energy of the \( J = 8 \) state in \( ^{46}\text{V} \) should be smaller than its analogue in \( ^{46}\text{Ti} \). This fact is consistent with the data but an interpretation in terms of alignments is not straightforward from Fig. 4.

For the highest spin states of band D we have also considered the possibility of a negative parity character. For this purpose and to study the regular negative parity bands E and F we have also performed SM calculations with the code ANTOINE in the full \( sd \) and \( pf \) valence space allowing for one hole in the \( d_{\frac{3}{2}} \) orbit as in ref. [10]. The SM calculations suggest that if the high spin states in band D were of negative parity, they should decay to bands E, F or G. We were not able, however, to observe such transitions. Further measurements are needed to give a definitive assignment to these levels.

In a self-conjugate nucleus such as \( ^{46}\text{V} \), a particle-hole excitation can be thought as a proton hole coupled to the g.s. band in \( ^{47}\text{Cr} \) and a neutron hole coupled to that in \( ^{47}\text{V} \). Since these two nuclei have \( J^g = \frac{3}{2}^- \) ground states, one would expect \( J^V = 0^- \) or \( J^V = 3^- \) for the band-head of the negative parity bands in \( ^{46}\text{V} \). Shell model calculations predict that the first three states \( (0^-, 1^-, 2^-) \) are almost degenerate. This can be understood by taking into account that the \( 1^- \) and \( 2^- \) states can also be built by coupling the \( d_{\frac{3}{2}} \) hole with the states \( J^V = \frac{5}{2}^- \) and \( J^V = \frac{5}{2}^- \) in \( ^{47}\text{V} \) or \( ^{47}\text{Cr} \), which are also almost degenerate with the g.s. \( J^V = \frac{3}{2}^- \). Finally, the backbending observed at \( J = 10 \) in \( ^{46}\text{V} \) is consistent with the backbending in the \( A = 47 \) mirrors at \( J = \frac{17}{2}^- \). Data are compared with SM calculations in Fig. 3b.

The SM predictions for the reduced transition amplitudes in bands E and F are in agreement with the experimental decay patterns. The branching ratios for electric quadrupole transitions connecting states with \( \Delta J = 1 \) are very small in comparison with those connecting \( \Delta J = 2 \) states. Moreover, the B(M1) values are less than \( 5 \times 10^{-3} \mu^2_n \) in all cases. The intrinsic quadrupole moments derived from the calculated static quadrupole moments and the \( B(E2) \) values are very similar at low spin and decrease very slowly up to the backbending, indicating rotational behaviour [3]. At high spin, the
$B(E2)$ values are consistent with a terminating band process. Both signatures terminate at the maximum spin which can be built in the $(f_7^2)^7(d_4^2)^{-1}$ configuration.

In summary, the level scheme of $^{46}$V has been greatly extended. Positive and negative parity $T = 0$ band structures have been identified and observed for the first time up to band termination. In addition, the isobaric analogue states of the $T = 1$ band in $^{46}$Ti are established to $J^\pi = 6^+$. Higher spin states, including the band terminating $J^\pi = 14^+$, which decay to the $T = 0$ band A are tentatively assigned to the $T = 1$ band. Excellent agreement is found between the experimental data and calculations. Pairing properties of each isospin channel are studied as a function of angular momentum.

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FIG. 1. Level scheme of $^{46}$V from the present work. Transition and level energies are given in keV.

![Level scheme of $^{46}$V](image)

FIG. 2. $\gamma$-ray spectra generated by setting coincidence gates in the $\gamma-\gamma$ kinematically Doppler corrected matrix. (a) The spectrum in coincidence with the 422 keV transition in the positive parity $T = 0$ band A. (b) The spectrum in coincidence with the 1098-keV transition in the negative parity band E.
FIG. 3. Excitation energy versus angular momentum for states in $^{46}$V. The experimental data (filled symbols) are compared with shell model calculations. (a) The $T=0$ and $T=1$ positive parity bands. (b) The $T=0$ negative parity band; the inset shows the experimental excitation energy, minus an average rigid rotor contribution, plotted separately for each signature.

FIG. 4. Pairing correlation energy versus angular momentum for the $T=1$ isobaric analogue states in $^{46}$V and $^{46}$Ti from SM calculations. (a) $T=1$ ($J=0$) pairing channels in $^{46}$V. (b) $T=1$ ($J=0$) pairing channels in $^{46}$Ti. (c) $T=1$ ($J=0$) and $T=0$ ($J=1$) pairing channels in $^{46}$V.

TABLE I. Reduced matrix elements for transitions between positive parity states in $^{46}$V from SM calculations.

| $I_i^\pi$ | $I_f^\pi$ | $B(M1)$ | $B(E2)$ | BR$_{theo}$ (%) | BR$_{exp}$ (%) |
|----------|----------|---------|---------|----------------|----------------|
| $1^{T=0}$ | $0^{T=1}$ | 1.07    |         |                |                |
| $2^{T=1}$ | $0^{T=1}$ | 142     |         |                |                |
| $3^{T=0}$ | $2^{T=1}$ | 0.15    |         |                |                |
| $4^{T=1}$ | $2^{T=1}$ | 187     | 10      |                |                |
| $3^{T=0}$ | $5^{T=0}$ | 0.63    | 82      | 100 (20)       |                |
| $5^{T=0}$ | $1^{T=1}$ | 0.03    | 7       |                |                |
| $6^{T=1}$ | $5^{T=0}$ | 0.77    | 42      | 100 (40)       |                |
| $5^{T=0}$ | $1^{T=1}$ | 0.49    | 57      |                |                |
| $4^{T=1}$ | $1^{T=1}$ | 175     | 1       |                |                |
| $8^{T=1}$ | $9^{T=0}$ | 1.02    | 63      |                |                |
| $7^{T=0}$ | $7^{T=0}$ | 1.40    | 28      |                |                |
| $7^{T=1}$ | $7^{T=0}$ | 0.017   | 7       | 100 (45)       |                |
| $6^{T=1}$ | $6^{T=1}$ | 167     | 2       |                |                |
| $12^{T=1}$| $13^{T=0}$| 2.56    | 0.4     | 21             |                |
| $11^{T=0}$| $11^{T=0}$| 1.21    | 1.4     | 78             | 100 (30)       |
| $10^{T=1}$| $10^{T=1}$| 54      | 1       |                |                |
| $14^{T=1}$| $15^{T=0}$| 3.19    | 98      | 100 (30)       |                |
| $13^{T=0}$| $13^{T=0}$| 0.048   | 1.5     |                |                |
| $12^{T=1}$| $12^{T=1}$| 53      | 0.5     |                |                |