

Band termination in the $N=Z$ odd-odd nucleus ^{46}V

S. M. Lenzi,¹ D. R. Napoli,² C. A. Ur,^{1,3} D. Bazzacco,¹ F. Brandolini,¹ J. A. Cameron,⁴ E. Caurier,⁵ G. de Angelis,² M. De Poli,² E. Farnea,² A. Gadea,² S. Hankonen,⁶ S. Lunardi,² G. Martínez-Pinedo,⁷ Zs. Podolyak,² A. Povos,⁸ C. Rossi Alvarez,¹ J. Sánchez-Solano,⁸ and H. Somacal²

¹*Dipartimento di Fisica and INFN, I-35131 Padova, Italy*

²*Laboratori Nazionali di Legnaro, INFN, I-35020 Legnaro, Italy*

³*H. Hulubei National Institute of Physics and Nuclear Engineering, Bucharest, Romania*

⁴*Department of Physics and Astronomy, McMaster University, Hamilton, Ontario, Canada L8S 4M1*

⁵*Physique Théorique, CRN, F-67037 Strasbourg, France*

⁶*Department of Physics, FIN 40351 Jyväskylä, Finland*

⁷*University of Aarhus, DK 8000 Aarhus, Denmark*

⁸*Departamento de Física Teórica C-XI, Universidad Autónoma de Madrid, E-28049 Madrid, Spain*

(Received 5 May 1999; published 20 July 1999)

High spin states in the odd-odd $N=Z$ nucleus ^{46}V have been identified. At low spin, the $T=1$ isobaric analog states of ^{46}Ti are established up to $I^\pi=6^+$. 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 $I^\pi=15^+$. Both signatures of a negative parity $T=0$ band are observed up to the terminating states at $I^\pi=16^-$ and $I^\pi=17^-$, respectively. The structure of this band is interpreted as a particle-hole excitation from the $1d_{3/2}$ shell. Spherical shell model calculations are found to be in excellent agreement with the experimental results. [S0556-2813(99)50708-5]

PACS number(s): 23.20.Lv, 27.40.+z, 21.60.Cs, 21.10.Hw

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 behavior is manifested in backbending and band termination phenomena. The $N=Z=24$ nucleus ^{48}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 $\beta \approx 0.28$ [1,2]. As one moves away from ^{48}Cr , the collective behavior 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 $|N-Z|$ [3]. 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 [4] and very recently ^{44}Ti [5]. Bandlike 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 $T=1$ $I^\pi=0^+$, 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, noncollective band-terminating states of natural parity have been reported recently in several nuclei in this shell [1,5]. 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 [6]. 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 [7]. The g.s. $T=1$ band, isobaric analog of the ground state (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 $T=1$ isobaric analog states of ^{46}Ti are established up to spin 6^+ . The energetically favored $T=0$ 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 $(d_{3/2})^{-1}(pf)^7$ configuration. This is the first time that both signatures of an unnatural parity band are observed up to the band termination in this mass

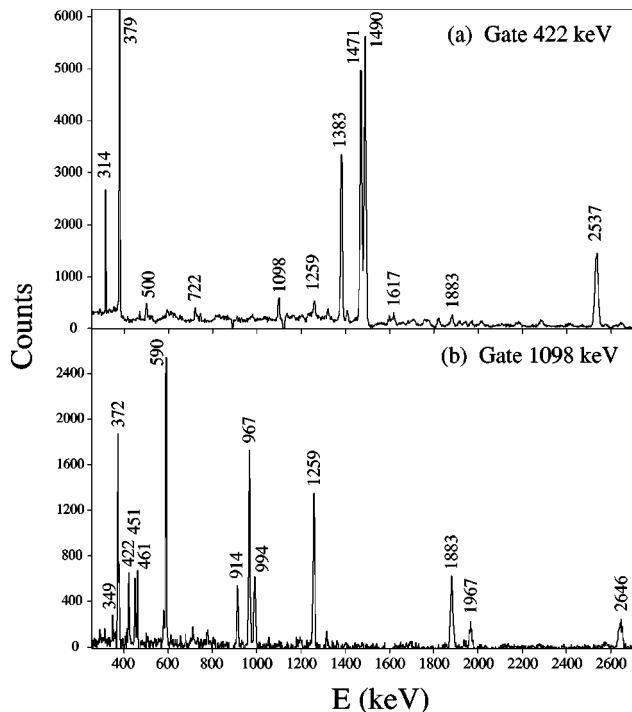


FIG. 2. γ -ray spectra generated by setting coincidence gates in the γ - γ kinematically Doppler corrected matrix. (a) The spectrum in coincidence with the 422 keV transition in the positive parity $T=0$ band A. (b) The spectrum in coincidence with the 1098-keV transition in the negative parity band E.

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 ^{46}Ti . 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 $f_{5/2}$ subshell which lies about 6 MeV above the $f_{7/2}$. On the basis of the DCO analysis we assign $J^\pi=16^+$ to the state at 11.753 MeV.

The 0^+ , 2^+ , 4^+ , and 6^+ states of band D in ^{46}V at excitation energies of 0, 915, 2054, and 3365 keV are interpreted as the $T=1$ isobaric analogs of the 0, 889, 2010, and 3300 keV states of ^{46}Ti . 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 $12^{(+)}$ and $14^{(+)}$ 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 ^{46}Ti . 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, and 1698 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 $f_{7/2}d_{3/2}^{-1}$ 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 $J \approx 10$ is evident from Fig. 1. Up to the backbending there is not signature splitting, as can be seen on the inset to Fig. 3(b). 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 favored way [11]. 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 the DCO analysis and decay pattern.

As stated above, shell model (SM) calculations in the full pf shell space have been shown to give a very good description of $f_{7/2}$ -shell nuclei. We have performed these calculations to study the positive parity states in ^{46}V with the code ANTOINE [12] using the KB3 interaction and the experimental single-particle energies of ^{41}Ca . The theoretical spectrum for the $T=0$ yrast band and the $T=1$ g.s. band of ^{46}V obtained from these calculations is compared with the experimental data in Fig. 3(a). 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 significant 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 calcu-

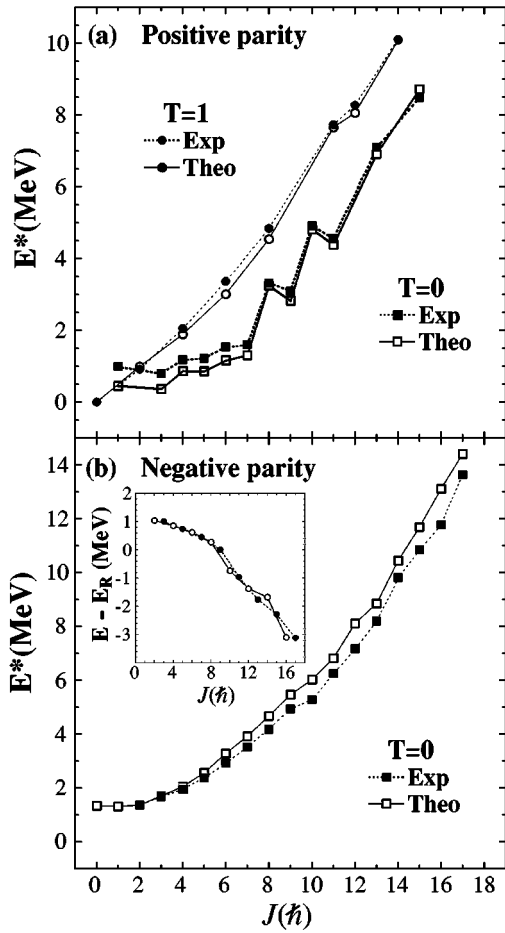


FIG. 3. Excitation energy versus angular momentum for states in ^{46}V . The experimental data (filled symbols) are compared with shell model calculations. (a) The $T=0$ and $T=1$ positive parity bands. (b) The $T=0$ negative parity band; the inset shows the experimental excitation energy, minus an average rigid rotor contribution, plotted separately for each signature.

lated [13]. We have calculated the expectation value of the pairing correlation energy in perturbation theory, as described in Ref. [14] for the $T=1$ isobaric analog states in ^{46}V and ^{46}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}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 behavior is found for ^{46}Ti , as shown in the middle of Fig. 4. The number of valence neutrons in ^{46}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

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

I_i^π	I_f^π	$B(M1)$ (μ_N^2)	$B(E2)$ ($e^2 \text{fm}^4$)	BR_{theo} (%)	BR_{exp} (%)
$1^{T=0}$	$0^{T=1}$	1.07	—	—	—
$2^{T=1}$	$0^{T=1}$	—	142	—	—
$3_2^{T=0}$	$2^{T=1}$	0.15	—	—	—
$4^{T=1}$	$2^{T=1}$	—	187	10	—
	$3_2^{T=0}$	0.63	—	82	100 (20)
	$5_1^{T=0}$	0.03	—	7	—
$6^{T=1}$	$5_2^{T=0}$	0.77	—	42	100 (40)
	$5_1^{T=0}$	0.49	—	57	—
	$4^{T=1}$	—	175	—1	—
$8^{T=1}$	$9_1^{T=0}$	1.02	—	63	—
	$7_2^{T=0}$	1.40	—	28	—
	$7_1^{T=0}$	0.017	—	7	100 (45)
	$6^{T=1}$	—	167	2	—
$12^{T=1}$	$13^{T=0}$	2.56	0.4	21	—
	$11^{T=0}$	1.21	1.4	78	100 (30)
	$10^{T=1}$	—	54	1	—
$14^{T=1}$	$15^{T=0}$	3.19	—	98	100 (30)
	$13^{T=0}$	0.048	—	1.5	—
	$12^{T=1}$	—	53	0.5	—

with increasing spin. On the other hand, the pn $T=1$ pairing strength in ^{46}Ti follows the same behavior of the like-nucleon pairs in ^{46}V . In the bottom of Fig. 4, the contributions of both $T=0$ and $T=1$ (pp, nn , and pn) pairing terms

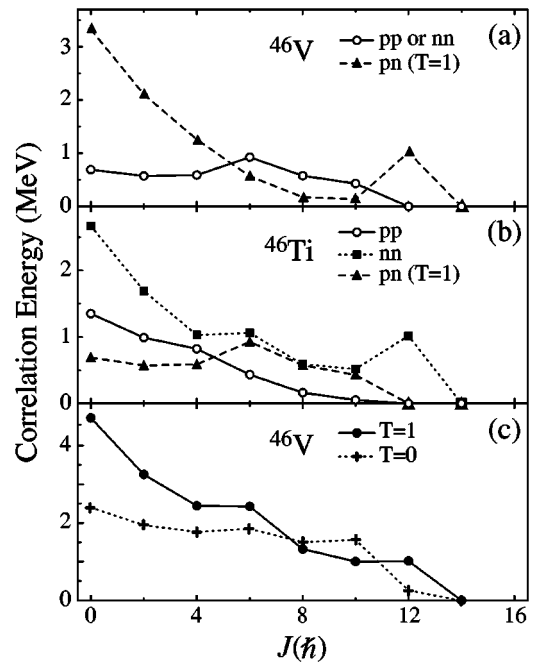


FIG. 4. Pairing correlation energy versus angular momentum for the $T=1$ isobaric analog states in ^{46}V and ^{46}Ti from SM calculations. (a) $T=1$ ($J=0$) pairing channels in ^{46}V . (b) $T=1$ ($J=0$) pairing channels in ^{46}Ti . (c) $T=1$ ($J=0$) and $T=0$ ($J=1$) pairing channels in ^{46}V .

are given for ^{46}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 $T=1$ analog states in ^{46}V are greater than those in ^{46}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}Ti , the Coulomb energy decreases, as has been pointed out in Ref. [15]. On the contrary, the alignment of pn pairs would not affect the Coulomb energy in ^{46}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}V should be *smaller* than its analog in ^{46}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 $d_{3/2}$ orbit as in Ref. [16]. 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}V , a particle-hole excitation can be thought of as a proton hole coupled to the g.s. band in ^{47}Cr and a neutron hole coupled to that in ^{47}V . Since these two nuclei have $J^\pi = \frac{3}{2}^-$ ground states, one would expect $J^\pi = 0^-$ or $J^\pi = 3^-$ spins for the bandhead of the negative parity bands in ^{46}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 $d_{3/2}$ hole with the states $J^\pi = \frac{5}{2}^-$ and $J^\pi = \frac{7}{2}^-$ in ^{47}V or ^{47}Cr , which are also almost degenerate with the g.s. $J^\pi = \frac{3}{2}^-$. Finally, the backbending observed at $J=10$ in ^{46}V is consistent with the backbending in the $A=47$ mirrors at $J = \frac{17}{2}$. Data are compared with SM calculations in Fig. 3(b).

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 $5 \times 10^{-3} \mu_N^2$ 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 behavior [2]. 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 $(f_{7/2})^7(d_{3/2})^{-1}$ 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 analog 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.

We are grateful to A. V. Afanasjev, M. A. Nagarajan, A. Vitturi, and R. Wyss for fruitful discussions.

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