High-spin behavior of multiple bands in the $N=Z+1$ nucleus ^{81}Zr : A possible probe of enhanced neutron-proton correlations

N. Mărginean,^{1,2} D. Bucurescu,¹ C. Rossi Alvarez,³ C. A. Ur,^{1,3} Y. Sun,^{4,5} D. Bazzacco,³ S. Lunardi,³ G. de Angelis,² M. Axiotis,² E. Farnea,³ A. Gadea,² M. Ionescu-Bujor,¹ A. Iordăchescu,¹ W. Krolas,⁶ Th. Kröll,⁷ S. M. Lenzi,³ T. Martinez,² R. Menegazzo,³ D. R. Napoli,² P. Pavan,³ Zs. Podolyak,⁸ M. De Poli,² B. Quintana,⁹ and P. Spolaore²

¹*H. Hulubei National Institute for Physics and Nuclear Engineering, Bucharest, Romania*

²*INFN, Laboratori Nazionali di Legnaro, Italy*

³*Dipartimento di Fisica dell'Università and INFN, Sezione di Padova, Italy*

⁴*Department of Physics, University of Notre Dame, Notre Dame, Indiana 46556, USA*

⁵*Department of Physics, Xuzhou Normal University, Xuzhou, Jiangsu 221009, People's Republic of China*

⁶*Institute of Nuclear Physics, Krakow, Poland*

⁷*Technische Universität München, Garching, Germany*

⁸*Department of Physics, University of Surrey, Guildford, United Kingdom*

⁹*Grupo de Física Nuclear, Universidad de Salamanca, Spain*

(Received 13 January 2004; published 5 May 2004)

A new experimental investigation of the level scheme of the $N=Z+1$ nucleus ^{81}Zr is reported. An additional band assigned to the $[431]1/2^+$ orbital has been observed and the known $[422]5/2^+$ and $[301]3/2^-$ bands have been extended to higher spins. The behavior of these bands is compared to that of the bands in the isotonic nucleus ^{79}Sr , for which some new experimental data are presented. Comparison is also made to the even-even $N=Z$ and $N=Z+2$ neighbors. The band structures are discussed in the framework of the projected shell model.

DOI: 10.1103/PhysRevC.69.054301

PACS number(s): 21.10.Re, 23.20.Lv, 25.70.Jj, 27.50.+e

I. INTRODUCTION

Despite a great deal of recent effort from both the experimental and theoretical sides, the $N \approx Z$ nuclei of the mass ~ 80 region remain relatively poorly understood, especially for the high spin states. This nuclear region exhibits a number of interesting phenomena, such as rapid structure changes (particle alignments, shape changes and shape coexistence) with changing mass number and angular momentum, and the possibility to search for the experimental signal of enhanced neutron-proton (np) correlations, especially in the pairing channel (both $T=1$ and $T=0$ modes). The most natural systems to study these np correlations are the $N=Z$ nuclei (the heaviest ones in particular) in which neutrons and protons occupy the same orbitals, and thus have the largest probability to form np pairs. Various calculations differ on the role played by the np correlation, nevertheless, for the even-even $N=Z$ nuclei one of the most conspicuous predicted effects is its influence on the band crossing, resulting in a delay of the crossing frequency at which the particle-alignment takes place.

A systematic delay of the alignment frequency (compared to the $N>Z$ nuclei from the same mass region) appears to occur for all even-even nuclei from ^{72}Kr to ^{88}Ru [1–4], although the backbending has not yet been observed in any of the nuclei above ^{72}Kr . In ^{72}Kr a delayed alignment was reported for the ground state band [1], and thought initially to be the effect of np pairing. More detailed subsequent studies of its band structures (Refs. [2,5–7]) have revealed a complex shape coexistence phenomenon in this nucleus. The analysis of Ref. [7] seems to rule out the need to invoke $T=0$ np pairing, and actually shows how difficult and delicate is the task of observing the possible effects of the np pairing,

particularly in nuclei with shape coexistence. In heavier $N=Z$ nuclei ($A \approx 80$) one has a well defined prolate shape. Competition with other shapes thus becomes less important. However, due to experimental difficulties, higher spin states in these nuclei have not yet been measured. It is therefore of interest to study experimentally other, more accessible systems, where shape coexistence phenomena are less probable.

In principle, the structure of the $N \approx Z$ nuclei should also be influenced by the np correlations, although this influence diminishes rapidly as T_z increases. The $N=Z+1$ nuclei, which are the closest to the $N=Z$ line, are obviously the best available probes and are easier to study since they are populated with larger cross sections.

Previous studies of the $N=Z+1$ nuclei in the heavier region, ^{75}Rb [8] and ^{79}Y [9], have addressed the problem of np pairing, and have shown that conventional TRS calculations (with only standard $T=1$ like-nucleon pairing) explain the available data (moments of inertia of two bands) rather well. Another study of a $N=Z+1$ nucleus, ^{73}Kr [10], has revealed a particular high spin behavior of one of its rotational bands which may indicate an effect of the $T=0$ np pairing, although this interpretation is not completely unambiguous.

One may characterize the situation of the present understanding of the $N \approx Z$ nuclei as follows.

In the region of the heavier $N \sim Z$ nuclei, the TRS calculations are generally successful in predicting crossing frequencies in the nuclei not too close to the $N=Z$ line. This may suggest that the np pairing is not very important in such nuclei. For the $N=Z$ nuclei the scarcer data do not allow a definite conclusion.

In principle, $T=0$ np pairing interactions may survive at higher spins because they are not influenced by the Coriolis anti-pairing effect. Nevertheless, it has been argued [11] that

the effects of such interactions might not show up in the experimental data.

Unambiguous conclusions are difficult to draw because details of the crossing frequencies and of the rotational alignments depend on many other factors, such as shape changes and/or shape coexistence, as well as triaxiality. In addition, deformations in these nuclei have been studied only theoretically, and have not been confirmed experimentally. The single particle energies, which often affect the quality of predicted spectra, are not optimized in this exotic mass region.

For the even-even $N=Z$ nuclei the theoretical calculations agree on a possible unique signature of the np pairing correlations, which defines a clear effect that must be searched for: a delayed band crossing. Such a consensus is missing for the $N=Z+1$ odd- A nuclei. From the theoretical point of view, it is not clear at present what is the true nature of the np correlations in nuclei near the $N=Z$ line and how these are revealed in different configurations in the rotational spectrum. Consequently, it is important to map better experimentally the structure of the $N=Z+1$ nuclei around mass 80.

The higher spin states in the back-bending region of interest are not known for any $N=Z+1$ nuclei above ^{77}Sr . The observation of multiple bands with different single-particle origins, in the same nucleus, is also important. The present work is devoted to the study of the ^{81}Zr nucleus, and reports for the first time three rotational band structures observed in a $N=Z+1$ nucleus with mass above 80. The crossing frequencies have been identified for two of these bands. The bands are first compared with those observed in the isotonic nucleus ^{79}Sr , and then are discussed in the framework of the projected shell model.

II. EXPERIMENT

A. Level scheme of ^{81}Zr

Excited states in the ^{81}Zr nucleus were first reported by our group in Ref. [12]. We have repeated measurements with the same reaction, $^{58}\text{Ni}+^{28}\text{Si}$ (90 MeV), with the main purpose of expanding the ground state band (gsb) of ^{84}Mo [3]. The experimental setup comprised the Ge array GASP, the charged particle ball ISIS, and the neutron detectors n-ring, whose performances were mentioned in Refs. [3,4]. In the newer experiment the target consisted of a stack of two 0.5 mg/cm^2 ^{58}Ni foils. The γ - γ - γ coincidence data has been added to the similar ones of the older experiment [12], thus resulting in increased statistics. Two improvements in the measurements have allowed a significant extension of the level scheme of ^{81}Zr (reached by the an channel). The first was the addition of the neutron detection. By studying the coincidences of the γ -rays with both charged particles and neutrons, one could find a new band structure clearly assigned to ^{81}Zr . The second improvement was a careful energy calibration of the Silicon particle detector telescopes of ISIS; this allowed a good kinematic correction of the Doppler broadening of the γ -rays, resulting in a better energy resolution.

Figure 1 shows the level scheme deduced from the present experiment, which updates the older scheme from Ref. [12]. Relative intensities of the γ -rays and information

on the multipolarity of transitions, when possible, are given in Table I. Examples of spectra showing the three band structures in ^{81}Zr as determined from the summed data of the two experiments are given in Fig. 2.

The two band structures (labeled as $[422]5/2^+$ and $[301]3/2^-$) observed in Ref. [12] have been confirmed and can be followed to higher spins in both signatures. As Table I shows, the angular distribution Legendre polynomial coefficients determined for the lower, stronger transitions, show clear dipole or quadrupole character. Assuming that these represent $M1$ or $E2$ transitions, and using (as in Ref. [12]) the strong similarity of these bands with those in ^{79}Sr [13,14], the spins and parities shown in both Fig. 1 and Table I are tentatively proposed.

Both signatures for the newly added band structure (labeled $[431]1/2^+$ in Fig. 1) have been observed. The angular distribution data for transitions in this band could not be analyzed due to the much smaller intensity of this band compared to that of the other two bands. The tentative spin and parity values of this new band structure have been proposed on the basis of its strong similarity to the $[431]1/2^+$ band known in the ^{79}Sr [13] and ^{81}Sr [15,16] neighboring nuclei.

The two transitions of 133 and 192 keV below this band structure have been observed with reduced intensity when gating on higher transitions in the two bands, an indication of the fact that both the $(1/2^+)$ and $(3/2^+)$ states have long lifetimes of the order of tens of ns. Most of the nuclei populated in these states decay after recoiling out of the center of GASP. A similar reduction in intensity has been found for the case of a known isomeric state in ^{79}Sr (177 keV, $5/2^+$, with a lifetime of 20 ns) [14,17], observed with GASP in the reaction $^{58}\text{Ni}+^{24}\text{Mg}$ (90 MeV). It has been assumed that the transitions of 133 and 192 keV feed the $3/2^-$ ground state [20]. The lifetimes of the 133 keV and 192 keV states have been estimated by comparing the experimental ratio between the intensity observed below and above the isomeric state, with the corresponding calculated ratio, in which the detection efficiency of GASP for the isomeric decay has been integrated over the whole recoiling path of the nuclei in a Monte Carlo simulation (similar to the recoil shadow anisotropy method [21]). From a spectrum gated by the 462 and 910 keV transitions, a value of 0.11(5) has been deduced for the intensity ratio of the 133 and 237 keV transitions deexciting and feeding, respectively, the 133 keV state. A similar value has been derived for the corresponding intensity ratio at the 192 keV state, however with a larger error due to the unknown contribution of the possible (unobserved) transition of 59 keV from the 192 keV state to the 133 keV state. These low precision intensity ratios allowed us to establish a lower limit of about 40 ns for the lifetimes of the 133 and 192 keV states.

For the $[422]5/2^+$ band, no transitions to the other two bands were found. Also, no transitions below the 303.3 keV transition were observed, which is an indication of low excitation energy and/or a longer lifetime of the $5/2^+$ state. This was left as a floating band, as in our previous work [12].

B. Level scheme of ^{79}Sr

The level scheme of ^{79}Sr has been previously investigated by heavy-ion reactions, leading to the observation of the

FIG. 1. Level scheme of ^{81}Zr as observed in our experiments. This level scheme supersedes that of Ref. [12]. The three band structures are labeled, for convenience, with the Nilsson assignments discussed in the text.

three band structures mentioned above [13,14,17]. Data from a previous experiment that we performed with the GASP array and the $^{58}\text{Ni} + ^{24}\text{Mg}$ reaction at 90 MeV [18] has made it possible to considerably extend the level scheme. Here we present only results relevant to the ^{81}Zr study. The complete results will be provided in a forthcoming publication [19]. Of interest for this work are the transitions added in the upper part of the three band structures. Figure 3 presents these three bands, which have all been extended to higher spins compared to the previous available data [13,14]. The observed high spin behavior will be discussed below in comparison with that of ^{81}Zr .

III. DISCUSSION

A. Qualitative discussion of band behavior

The Nilsson single-particle level scheme shows two large gaps at a quadrupole deformation of $\beta_2 \sim 0.4$ for nucleon numbers 38 and 40 [22]. At these large deformations, the Nilsson orbitals close to the Fermi level of our nuclei are

[422]5/2⁺, [301]3/2⁻ and [431]1/2⁺. These orbitals should therefore dominate the structure of the low-lying bands. Bands based on these three orbitals have been found in ^{79}Sr [13,14] and ^{81}Sr [16]. The three bands observed now in ^{81}Zr correspond also to these three assignments.

In this section we compare the rotational behavior of the three bands of ^{81}Zr with that of the similar bands of ^{79}Sr , as well as with that of the yrast bands (gsb) of the neighboring even-even nuclei. Figure 4 shows the dynamic moments of inertia ($J^{(2)}$) of these bands as a function of rotational frequency. $J^{(2)}$ has been chosen for this comparison because this quantity is very sensitive to the details of the alignments taking place along the bands. The [422]5/2⁺ band in ^{81}Zr is extremely similar to the gsb of ^{82}Zr , showing the sharp alignment of the $g_{9/2}$ proton pair at a frequency close to 0.6 MeV. The [301]3/2⁻ and [431]1/2⁺ bands, on the other hand, follow very closely (in their lower part) the evolution of the gsb of ^{80}Zr (known, unfortunately, only up to about $\hbar\omega = 0.55$ MeV). The [301]3/2⁻ band shows the proton pair alignment around 0.6 MeV. In ^{79}Sr , we observe a similar

TABLE I. Relative intensities of the γ -ray transitions assigned to ^{81}Zr (level scheme of Fig. 1). For some stronger transitions the angular distribution coefficient A_2/A_0 and A_4/A_0 are also given. Unless otherwise specified, the errors in energy are below 0.2 keV, except for the values without decimal, where the errors are larger than 0.5 keV.

$E_\gamma(\text{keV})$	I_γ	A_2/A_0	A_4/A_0	Assignment
Band [422]5/2 ⁺				
143.0	100(11)	-0.19(11)	0.06(21)	(7/2 ⁺) → (5/2 ⁺)
160.1	97(6)	-0.24(12)	-0.22(21)	(9/2 ⁺) → (7/2 ⁺)
242.4	5.8(4)	-0.03(30)	0.42(48)	(13/2 ⁺) → (11/2 ⁺)
289.4	7.1(5)			(17/2 ⁺) → (15/2 ⁺)
303.0	32(2)			(9/2 ⁺) → (5/2 ⁺)
434.1	24(2)	-0.40(13)	-0.06(28)	(11/2 ⁺) → (9/2 ⁺)
594.1	6.7(5)			(11/2 ⁺) → (7/2 ⁺)
596.8	5.2(5)			(15/2 ⁺) → (13/2 ⁺)
676.4	51(1)	0.20(10)	-0.12(15)	(13/2 ⁺) → (9/2 ⁺)
749.6	4.8(13)			(19/2 ⁺) → (17/2 ⁺)
839.2	11.3(11)			(15/2 ⁺) → (11/2 ⁺)
886.0	38(1)	0.30(15)	-0.25(23)	(17/2 ⁺) → (13/2 ⁺)
1039.0	8.0(7)			(19/2 ⁺) → (15/2 ⁺)
1064.8	23(1)	0.38(30)	0.33(44)	(21/2 ⁺) → (17/2 ⁺)
1073.5	10.2(4)			(29/2 ⁺) → (25/2 ⁺)
1124.7	17(1)			(25/2 ⁺) → (21/2 ⁺)
1182	3.8(11)			(23/2 ⁺) → (19/2 ⁺)
1189	2.7(11)			(33/2 ⁺) → (29/2 ⁺)
1391	2.1(6)			(37/2 ⁺) → (33/2 ⁺)
Band [301]3/2 ⁻				
167.2	46(3)	0.01(10)	0.02(17)	(5/2 ⁻) → (3/2 ⁻)
238.2(3)	50(2)	-0.18(11)	-0.07(18)	(7/2 ⁻) → (5/2 ⁻)
292.3	19(1)	-0.36(23)	-0.25(36)	(9/2 ⁻) → (7/2 ⁻)
367.5	11.3(5)	-0.27(20)	-0.06(33)	(11/2 ⁻) → (9/2 ⁻)
401.6	5.5(3)	-0.55(34)	-0.07(33)	(13/2 ⁻) → (11/2 ⁻)
405.4	18(2)			(7/2 ⁻) → (3/2 ⁻)
493.6	5.2(6)			(15/2 ⁻) → (13/2 ⁻)
530.4	23(1)	0.27(17)	-0.17(42)	(9/2 ⁻) → (5/2 ⁻)
659.6	17(1)	0.45(19)	0.19(24)	(11/2 ⁻) → (7/2 ⁻)
769.0	24(2)	0.25(22)	-0.02(35)	(13/2 ⁻) → (9/2 ⁻)
895.1	16(2)			(15/2 ⁻) → (11/2 ⁻)
987.8	14.2(13)			(17/2 ⁻) → (13/2 ⁻)
1109.2	12.6(10)			(19/2 ⁻) → (15/2 ⁻)
1181.0	9.6(11)			(21/2 ⁻) → (17/2 ⁻)
1253.8(4)	3.6(6)			(25/2 ⁻) → (21/2 ⁻)
1264.8(3)	5.6(6)			(23/2 ⁻) → (19/2 ⁻)
1338	4.8(11)			(27/2 ⁻) → (23/2 ⁻)
1355	3.0(1)			(29/2 ⁻) → (25/2 ⁻)
Band [431]1/2 ⁺				
133.4(4)	0.9(5)			(1/2 ⁺) → (3/2 ⁻)
178.0	7.0(17)			(5/2 ⁺) → (3/2 ⁺)
191.8	0.6(5)			(3/2 ⁺) → (3/2 ⁻)
236.8	7.9(17)			(5/2 ⁺) → (1/2 ⁺)
309.4	10.1(12)			(7/2 ⁺) → (3/2 ⁺)

TABLE I. (Continued.)

E_γ (keV)	I_γ	A_2/A_0	A_4/A_0	Assignment
331.0	1.8(3)			$(9/2^+) \rightarrow (7/2^+)$
462.2	7.8(12)			$(9/2^+) \rightarrow (5/2^+)$
525.7	10.1(6)			$(11/2^+) \rightarrow (7/2^+)$
696.0	5.0(9)			$(13/2^+) \rightarrow (9/2^+)$
742.5	8.7(7)			$(15/2^+) \rightarrow (11/2^+)$
910.0	3.2(15)			$(17/2^+) \rightarrow (13/2^+)$
958.8	7.2(9)			$(19/2^+) \rightarrow (15/2^+)$
1115(1)	2.0(10)			$(21/2^+) \rightarrow (17/2^+)$
1171.7(4)	3.8(6)			$(23/2^+) \rightarrow (19/2^+)$
1372	1.2(9)			$(27/2^+) \rightarrow (23/2^+)$

situation, with the $[422]5/2^+$ band behaving like the gsb of ^{80}Sr , and the $[301]3/2^-$ and $[431]1/2^+$ bands following the gsb of ^{78}Sr . The broad alignment displayed at 0.55–0.6 MeV is attributed to the $g_{9/2}$ proton pair. Figure 4 suggests that the $[301]3/2^-$ and $[431]1/2^+$ bands in these nuclei follow closely the behavior of the even-even core with one less neutron. This is very interesting in the case of $N=Z+1$ nuclei, in view of the scarcity of data for the $N=Z$ even-even nuclei, in which the alignment patterns are yet to be observed.

One should note the striking behavior of the $[431]1/2^+$ band of ^{81}Zr at higher spins (Fig. 4). While in ^{79}Sr this band behaves roughly like the $[301]3/2^-$ band and is very similar to the ^{78}Sr gsb, in ^{81}Zr no trace of alignment is found up to a frequency of about 0.68 MeV or maybe even higher, unlike the one seen in the $[301]3/2^-$ band. This band behaves like a rather rigid, rotational band (its $J^{(2)}$ values are almost constant and equal to the $J^{(1)}$ ones), up to the highest observed frequency. It remains a challenge to explain why the $g_{9/2}$ proton pair alignment is absent or much delayed in the

$[431]1/2^+$ band of ^{81}Zr . The decoupling parameter a of this rotational $K=1/2$ band, as determined from the energies of three consecutive levels with $\Delta J=1$, is almost constant, varying from about -0.30 to -0.43 for the spin values between $5/2$ and $23/2$, thus having an average value of $a=-0.38(6)$ in this spin interval. This value corresponds to an almost maximum mixing between the spherical orbitals $d_{5/2}$ and $g_{7/2}$ in the Nilsson wavefunction $[431]1/2^+$, with $C_{7/2}^2=0.483(8)$. By comparison, in the same spin interval, the decoupling parameter of the $[431]1/2^+$ band in ^{79}Sr is $a=-0.19(2)$, which leads to a smaller occupation of the $g_{7/2}$ orbital, $C_{7/2}^2=0.455(3)$. The larger mixing observed in ^{81}Zr indicates a lowering of the $g_{7/2}$ orbital with respect to the $d_{5/2}$ one, which may be an indication of an increased np interaction.

B. Comparison with projected shell model calculation

1. The model

In order to understand the rotational behavior of the observed band structures we have performed projected shell model (PSM) [23] calculations. The PSM has been extensively applied for a systematical study on the even-even $N=Z, Z+2$ and $Z+4$ Kr, Sr, and Zr nuclei [24], as well as the odd-odd $N=Z, Z+2$ and $Z+4$ Br, Rb, and Y nuclei [25]. Detailed analysis for the $N=Z$ Kr, Sr, and Zr [26] and Mo and Ru nuclei [3] has also been carried out by the PSM. A systematic discussion can be found in Ref. [27]. In addition, we have applied the PSM to the interpretation of the structure of an $N=Z+1$ nucleus from this mass region, ^{85}Mo [28]. However, except in the ^{85}Mo study, most of the previous PSM calculations in this mass region were restricted to the properties of the yrast band.

Calculations in terms of a spherical shell model for nuclei discussed in the present paper are not feasible. It is a big advantage for the PSM to use the deformed single particle basis supplemented with angular momentum projection. In this sense, the PSM is a shell model which employs a shell model space constructed in the deformed Nilsson basis [23]. Diagonalization at given angular momenta mixes various K -states originally from the Nilsson orbitals. The PSM is thus capable of describing the dynamical evolution along a rotational band such as particle alignment, giving rise to the

FIG. 2. Spectra demonstrating the band structures observed in ^{81}Zr (a) and (b): Sum of triple coincidence gates set on transitions assigned to the bands labeled as $[422]5/2^+$ and $[301]3/2^-$ respectively (Fig. 1), on a γ - γ - γ cube coincident with one α -particle and zero protons ($1\alpha 0p$); (c) spectrum gated by the 309 keV transition of the band $[431]1/2^+$ (Fig. 1) on a $1\alpha 0p$ γ - γ matrix.

FIG. 3. Partial level scheme of ^{79}Sr . Compared to the previous data [13,14] all three band structures have been extended to higher spins by one up to five more transitions. Note also that the $[431]1/2^+$ structure is connected now by six transitions to the other two bands, compared to the two previously known of 284 and 375 keV, respectively [13].

phenomenon of back-bending in moments of inertia.

The PSM wave function for odd-neutron nuclei is given as

$$\psi_M^{I\sigma} = \sum_{\kappa} f_K^{I\sigma} \hat{P}_{MK}^I |\phi_{\kappa}\rangle. \quad (1)$$

The index σ labels the states with the same angular momentum and κ the basis states given below. $\hat{P}_{MK}^I$ is the angular momentum projector. The basis states $|\phi_{\kappa}\rangle$ are spanned by the following set:

$$\{\alpha_{n_i}^{\dagger}|0\rangle, \alpha_{n_i}^{\dagger}\alpha_j^{\dagger}\alpha_k^{\dagger}|0\rangle\} \quad (2)$$

with $|0\rangle$ the quasiparticle (qp) vacuum determined by the Nilsson + BCS calculations. $\alpha_i^{\dagger}$ are the qp creation operators on the qp vacuum. Note that the 1-qp neutron states $\alpha_{n_i}^{\dagger}|0\rangle$ include, among others, the three neutron Nilsson orbitals

near the Fermi level as discussed at the beginning of this section, which are of both positive and negative parity. The 3-qp states are these 1-qp neutron states plus an additional quasiparticle pair. The basis (2) is the minimum set of states required for a description of the bands with the spin-alignment process. This projected basis for odd-neutron systems was first suggested in Ref. [29] and has been proven successful in the description of high spin behavior of rotational bands in odd-neutron nuclei.

The present calculations have been performed by using three major shells ($N=2,3,4$) for both neutrons and protons. For the interaction strengths we have used the same standard values as those used in all the previous PSM studies [3,24–28] for the same mass region. Thus, we have a consistent theoretical framework for even-even, odd-A, and odd-odd nuclei. The deformation parameters at which the shell model bases are constructed are the commonly accepted val-

FIG. 4. (Color online) Comparison between the behavior of the experimental band structures (dynamical moments of inertia) in ^{81}Zr and ^{79}Sr and that of the ground state bands in the neighboring even-even nuclei. The symbols represent the experimental data for the odd-mass nuclei: filled, for $\alpha = +1/2$, empty for $\alpha = -1/2$; the thick dashed lines represent the ground-state band for the even-even nuclei.

ues for these nuclei: $\varepsilon_2 = 0.30$ for ^{81}Zr , and $\varepsilon_2 = 0.36$ for ^{79}Sr , respectively.

2. Comparison with the data

The results from the PSM calculations are compared to the experimental data in Fig. 5, in a plot of the kinetic moment of inertia vs rotational frequency. Overall, the calculations describe reasonably well the bands observed in ^{81}Zr . The back-bending observed in the $[422]5/2^+$ band at a frequency of $0.55\text{--}0.6\text{ MeV}$ is rather well reproduced. The $\nu g_{9/2}$ orbital is blocked in this band. The back-bending is found to be due to the alignment of a pair of $g_{9/2}$ protons. The detailed PSM analysis shows that the proton qp pair from $g_{9/2}$ with $K=3/2$ and $5/2$ coupled to $K=1$ are involved in the alignment process. The $[301]3/2^-$ experimental data show the beginning of an up-bending just after 0.6 MeV , which is also correctly predicted by the PSM. The calculations suggest also that a band-crossing starts to develop in the $[431]1/2^+$ band at frequencies around 0.7 MeV .

On the other hand, the calculated moments of inertia for the $[301]3/2^-$ and $[431]1/2^+$ bands are about 20% too low in

FIG. 5. Comparison of the experimental band structures (kinematic moments of inertia) in ^{81}Zr and ^{79}Sr with predictions of the PSM. Filled symbols represent the experimental data, empty ones the PSM results; the circles are used for the $\alpha = +1/2$ signature, the squares for $\alpha = -1/2$.

the low-spin region as compared with the data. One might think that these two bands correspond to larger deformations than the $[422]5/2^+$ band. However, calculations in which the projected basis is built at larger quadrupole deformations (up to $\varepsilon_2 = 0.36$) do not significantly improve the results for these two bands. The fact that the PSM approach with the same effective interactions and configuration space has worked reasonably well for the yrast bands in many nuclei in this mass region [24,25,27], but now cannot account equally well for *all* the bands in one nucleus (in the ^{85}Mo study [28], the agreement for the negative parity band was also found worse than for the positive parity band), may indicate that there is *something* missing in the model. The most probable missing ingredient in the PSM could be the np correlations.

As already mentioned, theoretical investigations have suggested that the np correlations are important in the discussion of the rotational properties in $N \sim Z$ nuclei. Now the results discussed above may further suggest that the interaction does not equally affect the rotational behavior of various bands in the same nucleus. For example, the simultaneous occurrence of neutron and proton high- j pairs (here the $g_{9/2}$ neutrons and protons) in the shell model configuration implies that the np type interaction can be significant in the shell model states. If the np correlation is not properly constructed in a model, a good description cannot be expected. In the present version of the PSM theory, the np residual interaction is allowed only in the quadrupole-quadrupole channel, but not in the pairing channel (see discussions in

Ref. [26]). The current parameterization somehow favors a good description for the $[422]5/2^+$ band, but it is not as good for the others.

This may pose an interesting question with regard to the current understanding and treatment of the np interaction for the $N \sim Z$ nuclei. It was argued [30] that by applying the concept of spontaneous breaking of the isospin invariance, the neutron-proton interaction can be effectively considered in a theory with only neutron-neutron and proton-proton pairings, since one has a freedom to choose one particular direction in the isospin space. This means that with the renormalized pairing interactions between the like-nucleons in an effective Hamiltonian, one may be able to account for the $T=1$ part of the proton-neutron pairing. In fact, the previous PSM calculations for $N=Z$ nuclei have employed this concept implicitly [24,25]. However, the discussions here indicate that the renormalization that mimics the np pairing may not work equally well for *all* bands within one nucleus. The use of the extended quadrupole plus pairing force [31] that contains an isospin-invariant pairing may be helpful in understanding the problem.

^{81}Zr is a $N=Z+1$ nucleus that is a direct neighbor of the $N=Z$ line. As one can see in Fig. 5, for ^{79}Sr ($N=Z+3$), with the exception of the band crossing region in the $[422]5/2^+$ band, the behavior of all three bands is well reproduced by the PSM up to the highest measured spin, in contrast to the situation in ^{81}Zr . We note in particular that in ^{79}Sr , the same PSM calculations achieve a nearly equally good agreement in moments of inertia for all the three bands at the low-spin region. This may be qualitatively understood as when we leave away from the $N=Z$ line, the requirement for considering the np pairing is drastically smaller.

Nevertheless, the observed up-bending behavior in the $[422]5/2^+$ band in ^{79}Sr cannot be reproduced. This experimental band looks rather similar to the $[422]5/2^+$ band in the isotone ^{81}Zr , showing an up-bending in the moment of inertia around 0.6 MeV for both signatures. On the other hand, the predicted trend by the PSM is that of a broad alignment (almost smooth behavior of the moment of inertia), as expected from the behavior of the moments of inertia in the other two bands in ^{79}Sr ($[301]3/2^-$ and $[431]1/2^+$) as well as

from those in its even-even neighbors $^{78,80}\text{Sr}$ [24]. The behavior of this band cannot be described by the PSM, and this disagreement presents a considerable challenge for the theory.

IV. CONCLUSIONS

In this work we have reported a new investigation of the $N=Z+1$ nucleus ^{81}Zr , and new results for its isotone ^{79}Sr . For ^{81}Zr , the previously known $[422]5/2^+$ and $[301]3/2^-$ bands have been extended to higher spins, and the $[431]1/2^+$ intruder band has been identified. For ^{79}Sr the known bands have been followed to higher spins. The three bands in the $N=Z+1$ nucleus ^{81}Zr have been compared with the similar bands from ^{79}Sr . The $[431]1/2^+$ band in ^{81}Zr exhibits a peculiar behavior, without showing any alignment up to a rotational frequency of 0.68 MeV or even higher, unlike the one in ^{79}Sr which is similar to the $[301]3/2^-$ band. Standard PSM calculations, which have been successful when applied to many yrast bands in this mass region, are not able to describe the different bands with the same degree of success in the two isotones, with the agreement being notably poorer in the case of ^{81}Zr . These facts hint to a possible increased importance of the np interactions in the $N=Z+1$ nucleus, and suggest that it may be a sensitive probe of the np pairing. The adequate treatment of these interactions remains a challenge for the PSM. Work along these lines is in progress. From the experimental point of view, it remains as a very important and difficult task of the future, to characterize the nuclear deformation along the bands by lifetime measurements.

ACKNOWLEDGMENTS

The authors are grateful to S. M. Fischer for her careful reading of the manuscript. Some of us (N.M., D.B., M.I.-B., A.I., W.K., Zs.P., and B.Q.) acknowledge the support received within the European Contract No. HPRI-CT-1999-00083 - V Framework Programme. Y.S. acknowledges the support by the NSF under Contract No. PHY-0140324.

-
- [1] G. de Angelis *et al.*, Phys. Lett. B **415**, 217 (1997).
 - [2] S. M. Fischer *et al.*, Phys. Rev. Lett. **87**, 132501 (2001).
 - [3] N. Mărginean *et al.*, Phys. Rev. C **65**, 051303(R) (2002).
 - [4] N. Mărginean *et al.*, Phys. Rev. C **63**, 031303(R) (2001).
 - [5] N. S. Kelsall *et al.*, Phys. Rev. C **64**, 024309 (2001).
 - [6] E. Bouchez *et al.*, Phys. Rev. Lett. **90**, 082502 (2003).
 - [7] S. M. Fischer, C. J. Lister, and D. P. Balamuth, Phys. Rev. C **67**, 064318 (2003).
 - [8] C. J. Gross *et al.*, Phys. Rev. C **56**, R591 (1997).
 - [9] S. D. Paul *et al.*, Phys. Rev. C **58**, R3037 (1998).
 - [10] N. S. Kelsall *et al.*, Phys. Rev. C **65**, 044331 (2002).
 - [11] A. L. Goodman, Phys. Rev. C **63**, 044325 (2001).
 - [12] N. Mărginean *et al.*, Phys. Rev. C **61**, 024310 (2000).
 - [13] S. Suematsu *et al.* Kyushu Univ. Tandem Acc. Rept. 1991-1992, 1993, p. 72.
 - [14] J. Heese *et al.*, Phys. Rev. C **41**, 603 (1990).
 - [15] D. H. Smalley *et al.*, Nucl. Phys. A **611**, 96 (1996).
 - [16] E. F. Moore *et al.*, Phys. Rev. C **38**, 696 (1988).
 - [17] J. Mukai *et al.*, Z. Phys. A **342**, 393 (1992).
 - [18] D. Bucurescu *et al.*, Nucl. Phys. A **705**, 3 (2002).
 - [19] N. Mărginean *et al.* (unpublished).
 - [20] W. X. Huang *et al.*, Phys. Rev. C **59**, 2402 (1999).
 - [21] E. Gueorguieva *et al.*, Nucl. Instrum. Methods Phys. Res. A **474**, 132 (2001).
 - [22] W. Nazarewicz, J. Dudek, R. Bengtsson, T. Bengtsson, and I. Ragnarsson, Nucl. Phys. A **435**, 397 (1985).
 - [23] K. Hara and Y. Sun, Int. J. Mod. Phys. E **4**, 637 (1995).
 - [24] R. Palit, J. A. Sheikh, Y. Sun, and H. C. Jain, Nucl. Phys.

- A686**, 141 (2001).
- [25] R. Palit, J. A. Sheikh, Y. Sun, and H. C. Jain, Phys. Rev. C **67**, 014321 (2003).
- [26] Y. Sun and J. A. Sheikh, Phys. Rev. C **64**, 031302(R) (2001).
- [27] Y. Sun, Eur. Phys. J. A (to be published).
- [28] N. Mărginean *et al.*, Phys. Rev. C **65**, 034315 (2002).
- [29] K. Hara and Y. Sun, Nucl. Phys. **A537**, 77 (1992).
- [30] S. Frauendorf and J. A. Sheikh, Nucl. Phys. **A645**, 509 (1999).
- [31] M. Hasegawa and K. Kaneko, Phys. Rev. C **59**, 1449 (1999).