Band structure in ^{79}Y and the question of $T = 0$ pairing

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Abstract.
Excited states in the N=Z+1 nucleus ^{79}Y were identified using the reaction ^{28}Si(^{54}Fe, $p2n$)^{79}Y at a 200 MeV beam energy and an experimental set up consisting of an array of Ge detectors and the Recoil Mass Spectrometer at Oak Ridge National Laboratory. With the help of additional γ-γ coincidence data obtained with Gammasphere, these γ-rays were found to form a strongly-coupled rotational band with rigid-rotor-like behavior. Results of conventional Nilsson-Strutinsky cranked shell model calculations, which predict a deformation of $\beta_2 \sim 0.4$, are in excellent agreement with the properties of this band. Similar calculations for the neighboring N=Z and N=$Z+1$ nuclei are also in good agreement with experimental data. This suggests that the presence of the putative T=0 neutron-proton pairing does not significantly affect such simple observables as the moments of inertia of these bands at low spins.

INTRODUCTION

The structure of highly neutron defficient nuclei have recently become the subject of very active experimental and theoretical studies [1–4]. This is partly because of the richness of physical phenomena appearing in these nuclei such as shape coexistence, prolate-oblate shape mixing or shape transitions to name a few. Another important reason for such activities is that they can be understood with a variety of theoretical approaches, including the Monte Carlo shell model [5], symmetry-conserving models [6], as well as mean-field or algebraic methods [7,8]. Therefore, they provide excellent oppertunity to study effective nuclear forces and methods, approximations, and coupling schemes. However, the reason which makes them very attractive to study is the possibility of observing new effects due to the neutron proton intereaction namely the emergence of collective T=0 pairing phase. Due to particles occupying strongely overlapping orbital in nuclei closer to the N=Z line, one expects an enhancement of neutron-proton (np) pairing, including the exciting possibility of observing *np* superconductivity. However, despite vigorous investigation of this problem, we still face many questions and conceptual difficulties regarding the existence of a *np*-pairing phase, its fundamental building blocks, and its experimental signatures. For example, the shell-model adapts rigorous definition of the Cooper pairs in terms of isospin-spin (T, J) quantum numbers, but lacks a natural definition of the order parameter. In contrast, the mean-field approach offers a natural definition of the order parameter Δ, but is less rigorous concerning parametrization of the pairing interaction. One of the possible manifestations of the *np* pairing is the extra binding energy in $N{=}Z$ nuclei, known as the Wigner energy (see, e.g., [9,10] and references therein). Indeed, conventional mean-field models, which only allow for $T{=}1$, $|T_z|{=}1$ pairing irrespective of its form, systematically underbind $N{=}Z$ nuclei [11]. But a generalized mean-field approach, which also allows for the $T{=}0$ *np* pairing, can naturally account for this extra binding energy which is characterized by an $\sim|N-Z|$ behavior [12]. Similarly, detailed microscopic shell-model calculations that correctly reproduce the Wigner energy show that the Wigner energy is indeed due to $T{=}0$ interaction [9,10]. However, its structure is very complex when expressed in terms of isoscalar nucleonic pairs of various angular momenta [10].

Medium mass $N \sim Z$ nuclei perhaps offer the most favorable conditions for the manifestation of *np* pairing phase in nuclear matter mainly because of the large number of valence protons and neutrons. A recent study of ^{74}Rb [1] has already provided some evidence for the presence of (collective) $T{=}1$, $T_z{=}0$ pairing in the even-spin band based on its similarity to the ground-state band in ^{74}Kr, its isobaric analogue. It seems, however, that the odd-spin $T{=}0$ band in this nucleus reflects mostly the (non-collective) coupling of a pair of [431]3/2 neutron and proton orbitals. Although shell model Monte Carlo calculations [5] seem to support this interpretation, it is not entirely clear whether the structure of ^{74}Rb reflects collective or non-collective components of *np* pairing. Therefore, systematic experimental studies of heavy $N{\approx}Z$ nuclei are needed to provide more clear clues concerning the question of isoscalar *np* pairing. The present study of ^{79}Y is part of our systematic studies of $T_z{=}1/2$ nuclei [2–4]. Earlier reports of this work has been presented in refs. [13–15].

EXPERIMENTAL PROCEDURE

The results presented in this work have been obtained in two separate experiments. In the first experiment, γ-rays associated with ^{79}Y were identified at the Holifield Radioactive Ion Beam Facility (HRIBF) using the reaction ^{28}Si(^{54}Fe, $p2n$)^{79}Y at 200 MeV and a beam intensity of $\sim$10 pnA. The target consisted of a layer of 0.5 mg/cm^2 ^{28}Si evaporated onto a 1 mg/cm^2 Ta foil that faced the beam. The emitted γ rays were detected by an array of six segmented-Clover and four Compton-Suppressed HPGe detectors. The recoils were separated in different groups according to the mass to charge ratio using the the Recoil Mass Spectrometer (RMS) [16] at HRIBF and detected at the focal plane of RMS by Position Sensitive Avalanch Counter (PSAC).

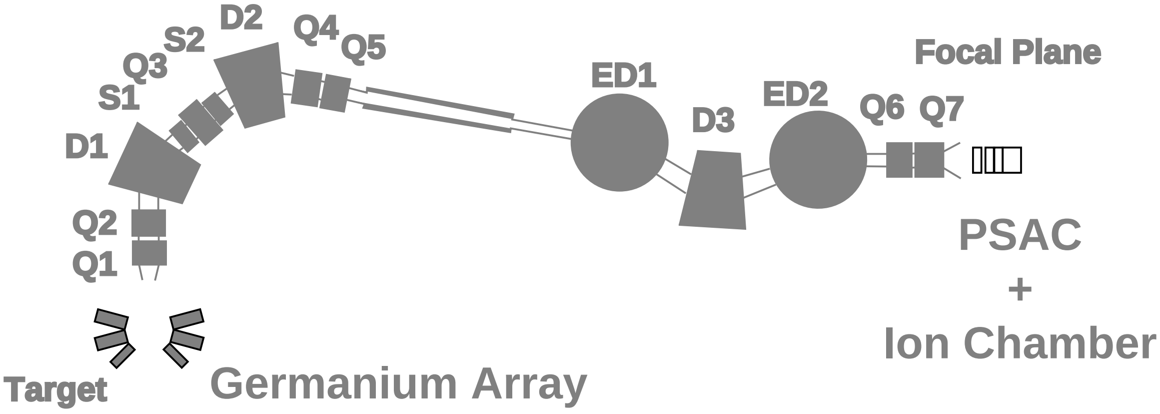

FIGURE 1. Schematic of experimental setup used to identify gamma-rays associated with ^{79}Y.

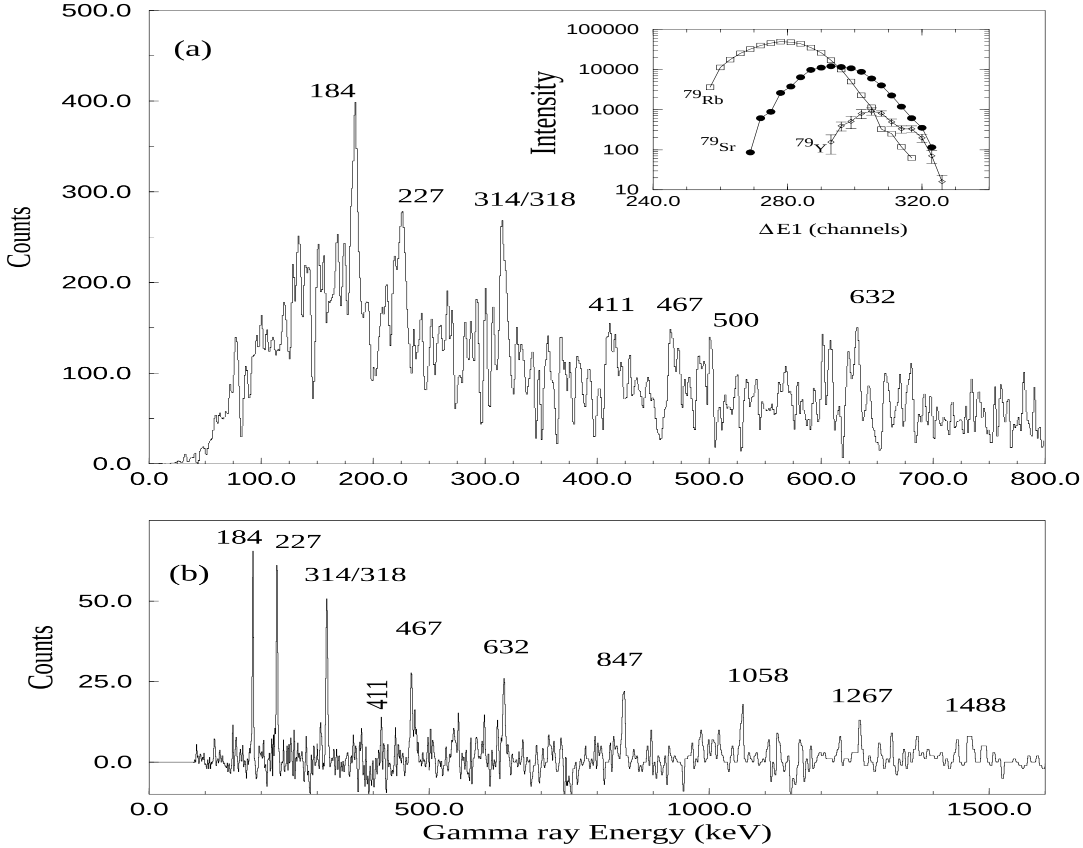

FIGURE 2. (a) A spectrum of characteristic γ rays in ^{79}Y ($N=Z+1$) gated with the RMS and ionization chamber at HRIBF. Gamma rays assigned to ^{79}Y have been marked by their energies in keV. Note that the 500 keV γ-ray is not placed in the level scheme. The inset shows the γ-ray intensity as a function of the energy-loss signal (ΔE) for ^{79}Rb, ^{79}Sr and ^{79}Y. (b) A spectrum obtained by summing several double gates on transitions belonging to the favored signature of the ground-state band in ^{79}Y.

The information regarding atomic number and total kinetic energy of recoiling nucleus is obtained by using Ionization Chamber [17]. Figure 1 shows the schematics of experimental setup. An inverse kinematic reaction which gives high center of mass recoil velocity, $\frac{v}{c} \sim 5.5\%$ was chosen so as to maximize focusing of recoils near 0^o and improve the Z resolution in an ionization chamber. All events were tagged by information regarding the mass and atomic numbers of the recoiling nuclei. Recoils with a mass of A=79 constituted $\approx$70% of all the recoils detected at the focal plane of the RMS. A total of 1.5×10^8 coincidences between one- and two-fold gamma-rays and the recoils were acquired. Schematic diagram of experimental setup is shown in Figure 1.

In the off-line analysis of these data, fusion-evaporation events were cleanly separated from those associated with beam scattering and pile up, by requiring that the recoils conform to the appropriate gates in a two-dimensional matrix of kinetic energy vs. mass-to-charge ratio (A/q) of the recoils. We also required that the two energy-loss (Δ E) signals obtained from the ionization chamber have the expected ratio for the recoils.

The later condition eliminated some contaminated events and improved the shape of the energy loss spectrum. Finally, after removing the energy dependence of the energy-loss signals, a two-dimensional matrix of ΔE vs. γ-ray energy was formed. Since ΔE signals provide information about the Z of the recoils, this matrix was used to identify the characteristic gamma rays associated with each of the reaction products.

The (A/q)-gated spectrum corresponding to mass A=79 contains four nuclei, namely ^{79}Rb ($3p$), ^{79}Sr ($2pn$), ^{79}Y ($p2n$) and ^{76}Kr ($\alpha 2p$). (The last nucleus appears in this gate due to the mass-to-charge ratio ambiguity.) With the help of a two-dimensional gate on the Total Energy vs. (A/q) matrix, a large fraction of the ^{76}Kr events was removed. The relative intensities of ^{79}Rb, ^{79}Sr, and ^{76}Kr in the mass-79 spectrum were 67%, 26%, and 6%, respectively. To identify the characteristic γ rays associated with the weakly populated nucleus ^{79}Y, we followed the following iterative procedure. First, using the known gamma rays in the strongly populated

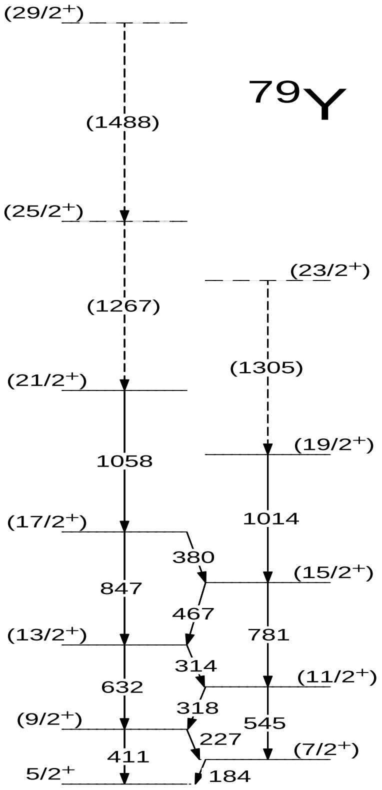

FIGURE 3. A partial level scheme for ^{79}Y obtained in the present work.

^{79}Rb and ^{79}Sr nuclei, we projected out their corresponding ΔE spectra. From both the shapes and centroids of these so-called Z spectra, we could determine the optimal ΔE gates for ^{79}Rb, ^{79}Sr, and ^{79}Y. In the second step, using these Z gates, we obtained total gamma-ray spectra for each of these three channels. The resulting spectrum for ^{79}Rb was free of contaminants, and was used to subtract out any contributions from this channel to the ^{79} Sr spectrum. Finally, a fraction of each of these two "purified" spectra were subtracted from the ^{79}Y spectrum to identify the characteristic gamma rays associated with this nucleus. The resulting γ-ray spectrum is shown in Fig. 2(a). In all, 6 γ-rays, 184 keV, 227 keV, 318 keV, 411 keV, 467 keV and 632 keV were assigned to ^{79}Y. Gamma-ray intensities as a function of the energy-loss signal in the ionization chamber confirmed that all these γ-rays belong to ^{79}Y. One such spectrum for the 184 keV transition is compared with those associated with γ rays in ^{79}Rb and ^{79}Sr in the inset of Fig. 2(a). We may define the quality factor for Z-resolution as $(P1 - P2)/FWHM$, where P1 and P2 are the centroids of the ΔE spectra for two isobaric nuclei with ΔZ=1 and FWHM is the full width at half maximum of these spectra. We obtained a quality factor of 0.7 for the present experiment. The partial cross section for ^{79}Y was estimated to be less than 200 μb.

In order to establish the coincidence relationship between the identified gamma rays in ^{79}Y, a γ-γ matrix and a γ-γ-γ cube were created from the data obtained in a second experiment using the reaction ^{58}Ni(^{28}Si, $\alpha p2n$)^{79}Y. The 130 MeV ^{28}Si beam was provided by the 88-Inch Cyclotron at the Lawrence Berkeley National Laboratory. Reaction γ-rays were detected by 57 Ge detectors of the Gammasphere Phase-I array [18], while charged particles were detected by 95 CsI detectors of Microball [19]. The target consisted of an enriched ^{58}Ni foil with a thickness of $\sim$0.4 mg/cm^2. A total of 1.5 × 10^9 events with a γ-ray coincidence fold of three or higher were collected. The level structure obtained from the analysis of these data is shown in Fig. 3. Lenz *et al.* [20] have previously reported a level structure for ^{79}Y. But, except for the pair of 184 and 227 keV transitions, our analysis did not find these gamma-rays to be in coincidence with each other. In accordance with the beta-decay results given in Ref. [21], we have adopted $5/2^+$ for the ground-state spin and parity. This is consistent with theoretical assignment of $g_{9/2}$ for the configuration of the ground-state band, as will be discussed below. Although lack of adequate statistics prevented us from confirming the tentative spin and parity assignments shown in Fig. 3, the presence of several interband transitions that connect the two signature partners of the band support our assignments for levels up to I^π=($17/2^+$). The 1488 keV (29/2 → 25/2) and 1267 keV (25/2 → 21/2) transitions in the favored signature of the band are shown as dotted because their placement could not be confirmed with respect to the 1058 keV (21/2 → 17/2) transition. However, our data indicate that they are in coincidence with other transitions in this band. Similar arguments hold for the 1305 keV (23/2 → 19/2) transition. Fig. 2(b) shows sum of spectra gated by 184, 227, 314, 318, 467, 632, and 847 keV transitions.

THEORETICAL INTERPRETATION

Figure 4(a) shows the experimental kinematic, $J^{(1)}[\equiv I/\omega]$ and dynamical, $J^{(2)}[\equiv dI/d\omega]$ moments of inertia (MoI) for the positive parity, positive signature $[(\pi,\alpha) = (+,+1/2)]$ band in ^{79}Y. As can be seen from this Figure, these two moment of inertias are nearly constant and equal ($J^{(1)} \sim J^{(2)} \sim 19\ \hbar^2\mathrm{MeV}^{-1}$) over the entire observed frequency range. The Moment of Inertia of a rigid spheroidal nucleus of mass A=79 and deformation of β_2=0.4 (as predicted by TRS calculations) is $J_{rig} \sim 22\ \hbar^2\ \mathrm{MeV}^{-1}$ which is slightly (∼ 10%) larger than what is observed in ^{79}Y. It has been pointed out previously that such an equality of kinematic and dynamic moments of inertia is a signature of rigid body like rotation [22]. Furthermore, Peker *et al.* [23] in their study of ^{98}Y have noticed $J^{(2)} \sim J_{rig}$ and have argued that this relationship signifies quenching of pairing correlations

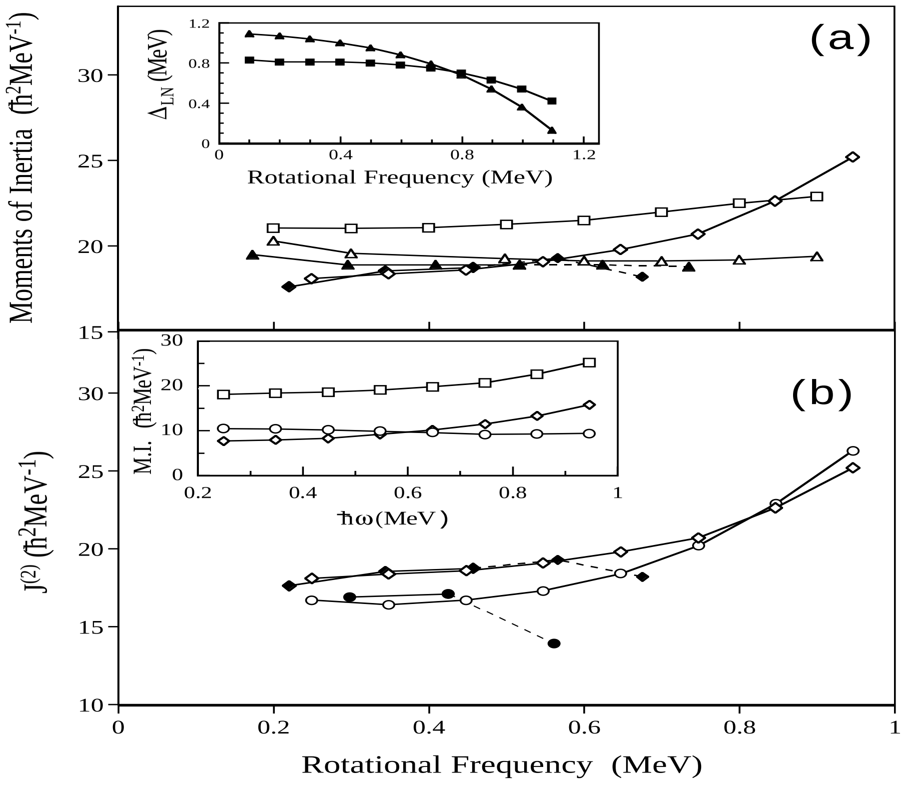

FIGURE 4. (a) Comparison of experimental (full symbols) and theoretical (open symbols) Moments of Inertia for the favored signature band in ^{79}Y as a function of $\hbar\omega$. The $J^{(1)}$ and $J^{(2)}$ moments of inertia are marked by triangles and diamonds, respectively. The open squares show the $J^{(1)}$ values from calculations with no pairing. The inset shows the pairing order parameters Δ_{LN} for protons (squares) and neutrons (triangles), respectively. (b) Comparison between the experimental (full symbols) and theoretical (open symbols) $J^{(2)}$ values for both signatures. The inset shows the $J^{(2)}$ contribution by neutrons (open diamonds) and protons (open circles) as predicted by theoretical calculations. The total $J^{(2)}$ contribution is shown by open squares.

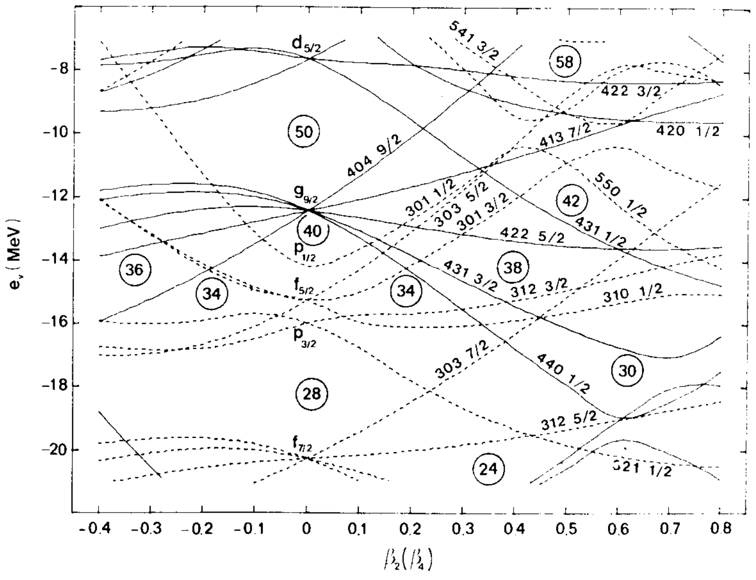

FIGURE 5. Single particle energy levels (Nilsson diagram) for nuclei in Mass-80 region

in ^{98}Y. As we shall see below, despite the fact that $J^{(2)}$ $\sim J_{rig}$, our detailed theoretical calculations points out the importance of pairing correlations in ^{79}Y.

To better understand the structure of the observed bands, we have performed deformation and pairing self-consistent Total Routhian Surface (TRS) calculations using a Saxon-Woods potential. The pairing channel includes seniority and doubly-stretched quadrupole pairing interactions to avoid spurious shape dependence. To avoid a superfluid-to-normal phase transition due to the mean field approximation, we employed an approximate particle-number projection known as Lipkin-Nogami method [25,26]. These calculations reveal that correct treatment of pairing is crucial for a quantitative understanding of the MoI despite the presence of large shell gaps that weaken pairing correlations. The role of pairing is illustrated in Fig. 4 where we have compared the calculated $J^{(1)}$ values for the paired (open triangles) and unpaired (open squares) systems. The calculated unpaired $J^{(1)}$ overestimates the experimental MoI by 2-3$\hbar^2$MeV^{-1}; i.e. by more than 10 % . The Lipkin-Nogami order parameters Δ_{LN} (i.e., the seniority type correlations) are shown in the inset of Fig. 4(a). They are weakly dependent on the rotational frequency below the point where $\nu g_{9/2}$ aligns and are $\Delta_{LN}^{(\pi)} \approx 0.8$ MeV and $\Delta_{LN}^{(\nu)} \approx 1.1$ MeV for protons and neutrons, respectively. These values may be compared with an estimate of the static pairing gap for this mass-region, namely $\Delta \approx 12/\sqrt{A} \approx 1.3$ MeV. Since Lipkin-Nogami order parameters take into account also the pairing fluctuations, indeed the calculated values of Δ_{LN} indicate weakened pairing correlations.

The fact of constancy of MoI in ^{79}Y is not unexpected and may be anticipated from the Nilsson diagram.(Please see Fig.5 for Nilsson diagram of the single-particle energies in this mass region.) The structure of the nucleus ^{79}Y (Z=39, N=40) is governed by the large shell gaps that appear at particle numbers N=38 and 40 at a deformation of $\beta_2 \sim 0.4$. These two gaps are bound by [431]3/2 on lower side and by [431]1/2 orbital on higher side and separated by Nilsson orbital [422]5/2 which is occupied by the unpaired proton in ^{79}Y at deformation of $\beta_2 \sim 0.4$. As a result of the [422]5/2 orbital occupancy of last proton, this orbital gets blocked and an effective *super*-gap at Z=38-40 gets formed. The formation of such a super gap thus facilitate the reduction of proton contribution to the pairing correlations in ^{79}Y. These observations are supported on quantitative basis by detailed theoretical calculations described above. Figure 4(c) shows calculated contribution of Proton and neutron to the dynamic moment of inertia $J^{(2)}$. As can be seen from Figure 4(c) and may be anticipated based on our discussion above, proton contribution remains nearly constant because of formation of an effective *super*-gap at Z=38-40 while the neutron contribution to $J^{(2)}$ increases with increasing rotational frequency. Results of the paired calculations for MoI are in excellent agreement with the data for both signatures as seen in Fig. 4. The detailed TRS calculations fully confirm all the anticipated trends. The ~10% difference between the unpaired value of the MoI and the data may be attributed to the presence of (weak) pairing correlations. Another important fact that emerges from these calculation is the stability of prolate deformed minima over observed frequency range. The calculated deformation ($\beta_2 \sim 0.4$) of the strongly-coupled yrast band built on

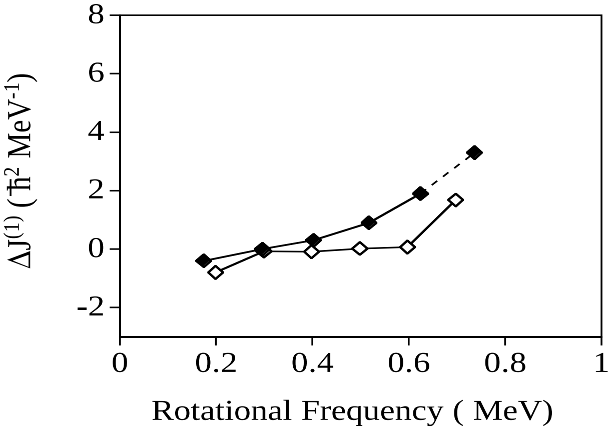

FIGURE 6. Comparison of the experimental (solid diamonds) and theoretical (open diamonds) differences of the moments of inertia, $\Delta J^{(1)} = J^{(1)}(^{77}Sr) - J^{(1)}(^{79}Y)$, as a function of rotational frequency for the positive-signature bands..

the $g_{9/2}$ proton orbital remains almost constant up to $\hbar\omega \approx$ 0.7 MeV. The stability of such a minima is an important consideration in present analysis since it eliminates the possible disagreement between theory and experiment which can be produced by effect such as shape variation or shape coexistence as these cannot be treated completely in mean field framework of our theoretical calculations.

The agreement between theory and experiment in ^{79}Y is remarkable. Our earlier studies in this mass region [2,3,24] have shown that the agreement is not accidental: Very good agreement between theory and experiment has been obtained also in the lighter T_z=1/2 nuclei ^{75}Rb [2] and ^{77}Sr [3]. As pointed out by Gross et.al. [2], for $T_z = \frac{1}{2}$ nucleus ^{75}Rb these calculations were able to reproduce observed experimental trends rather well. Although the calculated crossing is somewhat delayed compared to observed one, this can be attributed to the deficiency of cranking model in bandcrosssing region. It is also noteworthy that the ground-state band in ^{77}Sr (Z=38, N=39) shares many similarities with that in ^{79}Y: Occupation of the [422]5/2 orbital by the unpaired neutron creates a supergap at N=38-40 and deformation of $\beta_2 \sim 0.40$. Furthermore, the gap at Z=38 in ^{77}Sr closely resembles that at N=40 in ^{79}Y. Indeed, these two bands were found to be nearly identical both experimentally and theoretically. Figure 6 shows the differences in the values of $J^{(1)}$ for the ground-state bands in these two nuclei calculated from data and the theory. The agreement is again excellent.

Recently Satula et.al. have carried out Nilsson Strutinsky cranked shell model calculationsfor T=0 band observed in N=Z nucleus, ^{74}Rb. In these calculations, they could reproduce the observed feature of T=0 band (e.g routhians and moment of inertia) to a good accuracy.

It is rather unexpected that our conventional TRS calculations, which do not explicitly include the T=0 *np* interactions, can explain the experimental data in the $N \sim Z$ nuclei so well. (Some *np* interaction, however, enters into these calculations indirectly and through the assumption of common deformation for protons and neutrons. This interaction is of particle-hole type and can be well represented as a separable interaction in proton and neutron indices as discussed by Dobaczewski et. al. [27].) Two reasons may be suggested. First, such simple observables as the moments of inertia may not be sensitive to the presence of T=0 *np* interactions. Alternatively, effects due to the T=0 *np* interaction may manifest themselves more clearly at very high spins where Coriolis antipairing nearly quenches the T=1 interaction. Therefore, high-spin states in the N=Z nuclei may provide the best data set to look for T=0 pairing correlation.

FUTURE OUTLOOK

Encouraged by the success of mean field approach in this region in explaining the observed band structure, we hereby give prediction for N=Z nuclei ^{78}Y and ^{76}Sr [28]. As can be seen from Figure 7, for ^{78}Y the dynamic moment of inertia, $J^{(2)}$, remains constant for large frequency range again signifying the importance of blocking of orbitals $[422]\frac{5}{2}$ (see Figure 5) by last odd proton and odd neutron thus creating *super*gaps. In comparison, even-even, N=Z nuclei ^{76}Sr shows quite different behavior. The $J^{(2)}$ initially remains constant but after $\hbar\omega \sim$ 0.5 MeV shows increase in its value indicating the possible neutron alignment. These results are important because traditionally, it is believed that odd-odd N=Z nuclei are the most amenable to the *np* pairing thus forming important case for the test of the *np* pairing.

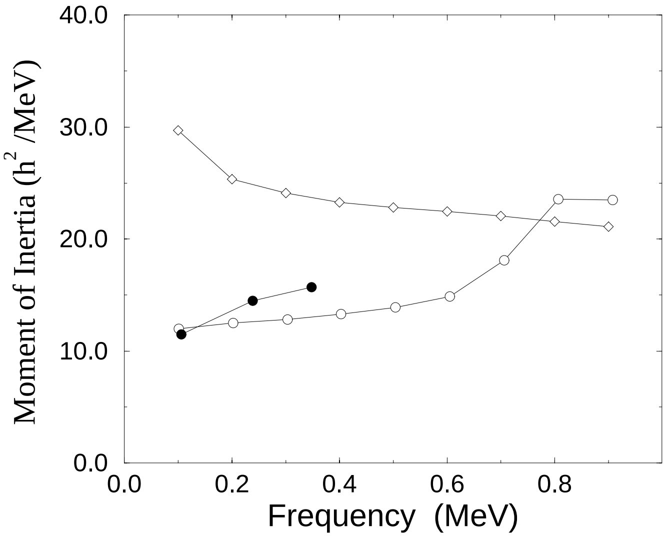

FIGURE 7. Predictions for heavy N=Z nuclei ^{78}Y (open diamonds) and ^{76}Sr (open circles). Experimental points for ^{76}Sr are shown in filled circles.

SUMMARY

To summarize, by combining data from two separate experiments we have identified a strongly-coupled band in the T_z=1/2 nucleus ^{79}Y which shows a rigid-rotor-like behavior. The favored and unfavored members of this band extend up to spins of $(29/2)\hbar$ and $(23/2)\hbar$, respectively. Conventional TRS calculations, which do not invoke any explicit T=0 proton-neutron correlations, are in excellent agreement with the experimental data for this nucleus, as well as its neighboring T_z=1/2 nuclei ^{75}Rb and ^{77}Sr. This suggests that the presence of the putative T=0 neutron-proton pairing does not significantly affect such simple observables as the moments of inertia of these bands. However, high-spin states in N=Z nuclei may provide some sensitivity to the effects of T=0 *np* interaction.

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